RELATION OF COMPACTION AND SOIL PHYSICAL PARAMETERS TO PRODUCTIVITY OF RECLAIMED SOILS

PROJECT GR896381

FINAL REPORT

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ABSTRACT

Compaction by heavy equipment during reclamation of surface-mined lands may affect soil physical parameters as bulk densities increase, porosity and pore sizes decrease. Water infiltration and permeability may decrease and rooting depth may be restricted among other factors affected. The objectives of this research were to determine the effects with time that various topsoil and subsoil tillage treatments (including chiselling, grader ripping and deep ripping) had on physical properties and yields, to determine the effects of prior cropping history on physical properties and small grain yield, and to determine long-term changes in physical properties on reclaimed mineland in North Dakota. Parameters measured included bulk density, soil strength, and yields of various forages and spring wheat. Results indicated that subsoil tillage treatments applied prior to topsoil respreading with scrapers were not effective in reducing bulk densities because the subsoil materials were recompacted during topsoil respreading. Although topsoil tillage treatments had significant effects on bulk density with time at some locations, the effects were not consistent among locations. Subsoil bulk densities and soil strength increased with time due to reconsolidation. Few significant tillage effects on forage or small grain yields were found although part of this was attributed to adverse growing-season weather conditions that prevailed during the time of this experiment. Rooting depths have not, as yet, been affected by the bulk densities and soil strengths measured and showed few significant tillage effects. Long-term locations have also shown some significant increases in bulk density with time. Freeze/thaw cycles have not affected bulk densities within the lower soil profiles because soil water levels are generally low in the fall. Prior cropping effects on small grain yields for the one year of data collected were generally not significant and were greatly

influenced by growing conditions. Overall the data indicated that the applied tillage treatments had few significant effects on bulk densities or soil strengths with time. Weather was the most dominant factor affecting both forage and small grain yields.

I. INTRODUCTION

Since the passage of the Surface Mining Control and Reclamation Act of 1977 (SMCRA), surface mine operators have become more aware of the deleterious effects of soil compaction on crop yields. Soil compaction may be defined as the compression of soil making it more dense (Gill, 1961). Thus, bulk density increases and fewer large pores are present. A compacted soil generally has poor aeration, low nutrient and water availability, slow permeability, and mechanical impedance to root growth (Raney et al., 1955).

Phillips and Kirkham (1962) have stated that soil strength measured with a penetrometer may be a better indicator than bulk density for root penetration since a penetrometer resembles the resistance a root may encounter. Thompson et al. (1987) found both bulk density and penetrometer resistance highly correlated to root length density in the lower portion of a reclaimed root zone.

Voorhees (1990) stated that freeze-thaw cycles failed to alleviate compaction caused by large farm machinery even nine years after the initial compaction. In arid climates such compaction may last even longer since soils in the fall generally contain insufficient amounts of soil water for frost heaving to occur (Brenneman, 1991).

One method that has been employed to alleviate soil compaction has been tillage. Subsoiling increased wheat yields significantly over non-ripped areas for two out of three years in one study (Barnhisel et al., 1988a). In a similar study, Barnhisel et al. (1988b) stated that ripping and/or subsoiling had no significant effect on bulk density and subsoiling generally reduced alfalfa yields. Meek et al. (1988) showed that traffic on the surface similar to what a producer would apply, reduced alfalfa yields by 10% compared to areas with no traffic. Compaction on 100%

of the surface after harvest each year reduced alfalfa yields by 17% compared to areas with no traffic.

One study by Materechera et al. (1992) evaluated the influence of a compacted subsoil on root characteristics of different plant species. Their data suggests that the size of a root has a significant influence on whether or not the compacted layers are penetrated. The study also showed that root tips were consistently larger for plants grown in compacted versus noncompacted subsoil.

Modeling efforts to describe compaction caused by mining equipment are now being done. In recent papers by Bingner and Wells (1992a and 1992b), compaction processes that are caused by equipment are described. Furthermore, their model allows several parameters to be changed to allow a better understanding of the soil compaction processes at surface mine sites.

II. OBJECTIVES

This study was undertaken to evaluate two major objectives. The first objective was to determine initial effects of various tillage treatments on alleviating compaction (reducing bulk density) following reclamation and to determine the effects with time these tillage practices had on physical properties (bulk density and soil strength), forage/small grain yields and root development. The second objective was to quantify the effects of root growth of various plant species and climatic factors on compaction (bulk density by depth) by analyzing mineland soils which had been reclaimed for several years. A secondary objective that was completed during the last year of this grant was to study the effect of three years of various forage species growth on spring wheat yields as compared to areas cropped yearly since reclamation was completed.

III. METHODS AND MATERIALS

Experimental sites for the topsoil/subsoil tillage treatment research were constructed in the fall of 1987 on the BNI Coal LTD. mine near Center and the Coteau Properties, North American Coal Corporation mine near Beulah, North Dakota. The site at Center was approximately 1 ha in size while the plot at Coteau was approximately 2 ha.

Subsoil was respread over 80% of each plot using scrapers applying the soil materials in 10 to 15 cm thicknesses (normal respread depths per scraper pass) followed by grading for surface leveling. The remaining 20% of each plot was replaced with scrapers utilizing minimum traffic patterns and no grading until sufficient subsoil was present to constitute the required depth (deep lift). A final grading operation across the entire plot completed the construction.

Following grading, the area of the plot (other than the deep lift area) was divided into four equal areas for further treatments (Figure 1). Tillage treatments were then applied on three strips across the plots, the other ones remained untilled (no till).

Topsoil was then respread on the entire plot in a manner similar to the subsoil respreading operation. After a final grading, the plots were subdivided into three blocks which were further subdivided into three topsoil tillage strips. Topsoil tillage treatments were randomly assigned within each block and applied perpendicular to the subsoil tillage treatments. The same equipment used for the subsoil tillage treatments was used for the topsoil tillage treatments. The characteristics of these treatments are listed in Tables 1 and 2.

The average depth of the respread topsoil and subsoil at the Center location was 33 and 90 cm, respectively. At Coteau the mean depth of respread topsoil was 41 cm and the mean depth of the subsoil was 79 cm. The topsoil by subsoil tillage subplots at Center were 21.3 by 6.4 m while at Coteau the subplots were 30.4 by 15.2 m.

Experimental sites for the topsoil tillage/forage research were established in the spring of 1989 at the Basin Cooperative Services Glenharold mine near Stanton and the Knife River Coal Mining Company South Beulah mine near Beulah, North Dakota. Both locations had been respread the previous fall using scrapers respreading an average depth of 0.3 m of topsoil and 0.6 m of subsoil. Each site was approximately 0.5 ha in size.

Surface tillage treatments were applied in strips at each location (Figure 2). The characteristics of the chisel and subsoiling operations are listed in Table 3. Following the initial tillage treatment, each site was lightly disked and harrowed after 112 kg/ha of ammonium nitrate was broadcast on the surface.

Each site was divided into two equal-sized blocks which were subsequently divided into six equal-sized strips perpendicular to the tillage treatments. Five forage crops (mixes and monocultures) and spring wheat (Stoa) were seeded into the strips (Figure 2). Crop by tillage treatment subplots were 12.8 by 7.3 m at Glenharold and 12.8 by 9.7 at Knife River.

Seeding mixtures and rates for the four locations are listed in Table 4. All seeding operations, except for the spring wheat, were performed by mining personnel and equipment. Because of poor germination and growth due to hot, droughty conditions in 1988, the topsoil/subsoil tillage sites were reseeded in 1989 after a light disking.

Soil fertility samples were made each fall on the spring wheat strips prior to a fall chiselling operation. Fertilizer was broadcast the following spring (prior to seeding) to produce a 2.7 Mg/ha crop for the first three years of the experiment. Half of the forage strips were chiselled in the fall of 1991 (Fig. 2) after three years' growth. Only one block at each site was fertilized for the small grain crop in 1992.

Access tubes for soil water monitoring to a depth of 1.5 m with neutron attenuation probes were installed in all or some of the subplots as shown in Figs. 1 and 2. Tubes were installed in the fall of 1987 at the topsoil/subsoil tillage sites (including the deep rip shank tracks) prior to seeding and in the spring of 1989 at the topsoil tillage/forage plots after seeding was completed. Soil water was measured biweekly at all sites.

Soil cores removed during access tube installation in 1987 were sampled in 15-cm depth increment samples for the two topsoil/subsoil tillage sites. Soil cores were sampled in 30 cm increments for the topsoil tillage/forage sites in 1989 and when additional tubes were installed in 1992. The soil samples removed were analyzed for bulk density, particle size, and chemical characteristics (pH, electrical conductivity and SAR). Estimated wilting points were calculated for each 30-cm depth increment using the soil materials removed and a pressure plate apparatus.

All bulk density measurements were conducted using a hydraulic coring machine. Cores were enclosed in plastic bags in the field, transported to the laboratory, weighed, dried at 104° C for 48 h, and reweighed. Bulk density (both wet and dry) was calculated by dividing the weight of the core by the volume of the core.

Forage yields at the various sites were generally taken in June of each year. This was based upon a 10-20% bloom of alfalfa in the plots. Samples were harvested by hand from 1 m^2 areas in each subplot, dried at 60° C for 48 h and then weighed. Small grain yields were also harvested by hand in each subplot from a 4 m^2 area. Following both forage and small grain harvests, all remaining forages and small grains from the subplots were mechanically harvested either by research or mining personnel or by cooperating farmers.

Beginning in the spring of 1990, and each subsequent spring, soil strength in all the subplots was measured with a hydraulically-driven cone penetrometer to a depth of 1 m. The penetrometer cone had a basal area of 506 mm^2 for 1990 only. Because of the difficulty encountered due to high soil strengths in penetrating the soil profile to a depth of 1 m, the cone basal area was reduced to 285 mm^2 for data collection in 1991 and 1992. Soil cores were removed adjacent to the cone penetrometer areas in 15 cm depth increments for bulk density and soil water determinations. The values were used to correlate the effect these variables had on the measured soil strength values.

All site data was analyzed as a nonrandomized modified split block design with technical statistical designs formulated after consultation with statisticians from North Dakota State University. All analyses including analysis of variance (ANOVA) and correlation/regression procedures were done with SAS (1990).

Least significant difference (LSD) values were calculated from the ANOVA outputs to delineate statistical differences among mean values where sample sizes were the same. For comparison among mean values of different sample sizes, individual comparisons between pairs of means were done using LSD values weighted for the differences in sample sizes. The level of significance (P) was generally set at the 10% level. Sample means were considered significantly different if the difference between the two means exceeded the LSD value. If the level of significance in the ANOVA output exceeded the 10% level, the mean values were treated as equal statistically and not significantly different (NS). Variables with the correlation/regression analyses were also subjected to a P level of 10%. Variables were included in the reported models only if their significant level was 10% or less.

Beginning in the fall of 1989, rooting characteristics of the alfalfa or forage grasses (depending upon location) were measured. Soil cores (15-cm long, 6-cm in diameter) were removed directly over the top of the plant to the depth of root penetration. The upper 0 to 5 cm of the first sample was discarded to remove crown effects. The soil was washed off the roots and root length was determined by hand (large taproots) and/or an electronic image analyzer. Root mass was determined by drying the roots at 70° C for 24 hours before weighing. Root length density was calculated by dividing the total length of roots by the sample volume. Root mass density was calculated similarly using root weights or is listed as total mass per sample (see units used).

Three locations where bulk density by depth had been measured several years previously were used to determine changes in bulk density with time. One location, the Falkirk trench site, had been excavated to a depth of 4.6 m in 1979 and reclaimed with various subsoil textures and topsoil depths. This site was cropped from 1980 through 1983 and has been seeded to a forage mixture since 1984. A detailed description may be found elsewhere (Halvorson et al., 1986).

The other two locations had been used since 1986 for a study on the effect of topography on forage and small grain yields. These sites were located on the BNI Ltd. mine near Center, North Dakota and the North American Coal Corporation Falkirk mine near Washburn, North Dakota. The Center location was reclaimed in 1983 while the Falkirk location was reclaimed in 1984. Detailed descriptions of the two locations are given elsewhere (Schroeder, 1991).

Soil bulk density by depth at these three locations were measured using the previously described soil core method. ANOVA models used to analyze time effects were a split split-block design at the Falkirk trench location and a single-factor block design at the two topography locations.

IV. RESULTS AND DISCUSSION

The primary textures of the soils at the tillage locations were loam and sandy loam. No deleterious chemical properties were found within the soil depths monitored that would have affected the crops grown on the plots. Detailed physical and chemical properties of each site are listed in the Appendix (Tables A1-A4).

Rain gauges were installed prior to or at small grain planting at the Glenharold and Knife River sites. A nearby rain gauge (1.5 km from site) was used at Center. No rain gauge was installed at Coteau. Generally, measured rainfall at all sites with time was below normal (Table 5). This factor plus high temperatures and the distribution of this rainfall (majority was received in amounts less than 1 cm/day or more than 4 cm/day) had major effects on crop growth and other related factors which will be discussed later.

For ease of discussion, results will be presented by separating the topsoil/subsoil tillage sites from the topsoil tillage/forage sites. This was done because of difference in tillage treatments and crops at the sites.

A. Topsoil/Subsoil Tillage Locations

1. Bulk Density

Initial bulk densities sampled in 15-cm depth increments are listed in Tables 6 and 7. As can be seen in the data, few significant differences were found in 1987 following the tillage applications. Subsoil was recompacted by the scrapers during the topsoil respreading operations. Some compaction of the topsoil occurred during a rock-picking operation and also during seeedbed preparation (disking) and seeding.

At both locations the significant differences that did occur were associated with the deep rip tillage treatment. However, there was a large amount of variability in all sample values which also contributed to the general lack of significant differences. The large variability and general lack of significant differences were the main reasons why 30-cm depth increments were used for all sampling dates thereafter.

One other observation can also be seen in Tables 6 and 7. In several instances the combination of tillage and the topsoil respreading operation by scrapers resulted in higher subsoil bulk densities than the area where no treatment was applied. This indicated that by loosening and then applying a compactive pressure, subsoil materials were compacted even more than that caused during the initial respreading and leveling operations. This was not completely unexpected since a similar type procedure (spreading, tilling, packing) is used in roadway-base construction to ensure a stable base.

Some of the topsoil tillage effects near the surface were still present 3 or 4 years after application (Tables 8 and 9). Again, most of these were associated with the deep rip tillage treatment (Appendix Table A5). This was also the general case for subsoil bulk densities (Appendix Table A6). Topsoil tillage effects below 0.6 m at Coteau and subsoil tillage effects in the 0-0.3 m depth at either location were generally the result of variation in the data. At Center, however, topsoil tillage for the deep rip treatment did have some effect to the depths sampled.

By the fall of 1991 at Coteau and the fall of 1992 at Center, no significant tillage effects on bulk density were found (Appendix Tables A5 and A6). This result indicated that tillage effects are temporary at best. However, this temporary effect may last long enough to affect other factors such as rooting depth and may have been the case here under better growing conditions.

Yearly changes in bulk density averaged over all tillage treatments by depth are illustrated in Fig. 3. The trend in the 0-0.3 m depth was a decreasing one until fall values for 1992 at Center and 1991 at Coteau (plot discontinued at that point due to construction of a conveyor system across the plot). The increase at Center in the fall of 1992 was significant while the increase at Coteau was not. These increases were attributed to surface traffic from sampling and forage harvest plus very dry soil conditions.

Yearly changes in the other three depth increments showed a general increase in bulk density with time. For several depths at these two locations, this increase in bulk density resulted in bulk density values significantly greater than those measured in 1987 (Table 10). The largest changes in these bulk densities generally occurred within the first three years of the experiment (actual values are listed in Appendix Table A7). The increases in bulk density were attributed to reconsolidation (settling) of the subsoil materials with time plus a continual reduction of soil water (discussed later).

These changes with time also resulted in many significant interaction terms in the ANOVA model for the various depth increments as shown in Table 10. The significant interaction terms indicate that changes within the profile are not occurring uniformly across the entire plot. Changes varied with time and tillage at both locations due to variability in the data for the individual sampling dates, reconsolidation rate changes, and soil water differences. Some of these changes can be seen (or concluded) from the data listed in Appendix Tables A5 and A6.

Attempts at extracting soil cores from the deep rip topsoil tillage shank tracks were not always satisfactory due to the loose materials in the shank tracks. Therefore, no report on this unreliable data will be given. Other data taken will, however, be discussed later in this report.

2. <u>Soil Strength</u>

Figure 4 illustrates an example of the yearly penetrometer measurements taken at each location. Careful examination of the subsoil data shows several peaks and valleys. These are spaced about 15 to 20 cm apart, the approximate thickness of the subsoil applied during one scraper pass. Thus it can be readily seen how compaction occurs during the spreading of soil materials by scrapers.

Significant differences (or lack thereof) in mean cone index values by tillage depths at the Center and Coteau locations are listed in Table 11. Nearly all instances of significant topsoil tillage effects were due to the deep rip treatment. As described previously, recompaction of the subsoil during topsoil respreading plus reconsolidation with time generally resulted in no significant subsoil tillage effects at either location. Variability in the data was high for most years and this caused significant subsoil tillage effects within the topsoil at the Center location in 1990. Yearly values for the two locations are listed in Appendix Tables A8 and A9.

It should be noted, however, that statistically significant differences in cone index values as a result of the initial topsoil tillage treatments were still present in the topsoil at both locations after several years. Bulk density values for these dates were not significantly different as mentioned previously. Since these values are means, the amount of variability in the data may have contributed to this. No differences, generally, were found within the subsoil (profile depth

> 30 cm) at either location which agreed also with the lack of differences in bulk density discussed earlier.

Cone index values increased significantly from 1990 to 1991 at both locations except for the 65 to 100 cm profile depth segment at Center (Tables 12 and 13). No significant change from 1991 to 1992 was found for the Center location. These changes are illustrated in Figures 5 and 6 (mean values by depth increments are listed in Appendix Tables A8 and A9). The increases in cone index values were attributed to the changes measured for bulk density plus data variability since few significant differences for volumetric soil water content except near the surface were found (Appendix Table A12).

Because the deep-rip topsoil tillage treatment shank tracks (DRSH) were marked, comparisons of between and within the shank tracks were also made. The upper 20 cm at both locations was analyzed separately to delineate traffic effects. Yearly ANOVA significance levels are also listed in Table 11. Differences were found at both locations for all years. Although the shank tracks had refilled with soil materials, the soil materials did not reconsolidate to the extent of the soil materials between the shank tracks. Differences in cone index values for this treatment between the two locations (Appendix Tables A10 and A11) were attributed to the differences in the shank size and depth of the methodology used to apply this treatment (Tables 1 and 2 in Methods and Materials).

Changes with time for the deep-ripped topsoil tillage plots are also illustrated in Figures 5 and 6 (Appendix Tables A10 and A11 list actual values). Although shank track cone index values have increased with time at both locations, these values have not increased as much as the value for between the shank tracks. Generally, the mean cone index values for the shank tracks remain significantly smaller than those for between the tracks. This again indicates that reconsolidation within the shank tracks has not occurred as rapidly as it has occurred for the soil materials between the shank tracks.

Correlation/regression analyses were done using mean cone index values for each 15-cm depth segment as the dependent variable. Independent variables included percentages of sand, silt, clay, very fine sand, very fine sand plus silt, gravimetric soil water content, volumetric soil water content, and dry and wet bulk density values. Individual yearly values were highly variable and will not be reported.

Results from the analyses reflected in the topsoil and subsoil fractions of the reclaimed profiles for over years at Center and Coteau are listed in Table 14. None of the analyses had coefficient of determination (R^2) values greater than 0.50. This was due to the large amount of variability in the data. Dry bulk density (DBD) was a significant parameter in each analysis because its effect on soil strength (as measured with the cone index values) indicated the close packing of the soil particles. In a similar manner, increasing soil water increased wet bulk density (WBD) and gravimetric soil water content (GRAVPC) which tended to decrease mean cone index values. As the soil materials become drier, the soil particles move closer together thus increasing DBD. As they become wetter, WBD increased with soil particles moving apart. In addition, the increased soil water (GRAVPC) will tend to help lubricate the contact between the penetrometer cone and soil particle surfaces. The influence of particle size on mean cone index values was neither consistent or major (as denoted by the small coefficients) at either location and was probably affected by the variations in the data sets. It may also have been due to compaction efforts as discussed later.

Table 15 shows the yearly and combined results from the two locations without separating the topsoil from the subsoil. The R^2 values were generally larger than those listed in Table 14. Again, the only consistent independent variable in all the models was DBD which affects the mean cone index values in the manner described previously. Similar soil water contents at Center in 1990 and 1991 were reflected in the absence of any soil water variable appearing in the model. GRAVPC was significant in 1992 at Center and for both 1990 and 1991 at Coteau even though the mean yearly values were not significantly different for most of the profile (Appendix Table A12).

Also, as for the topsoil and subsoil data in Table 14, particle sizes did not have consistent or major effects as mean cone index values. Again, this was probably due to variations in the data sets. It may also have been due to the effect of the compactive effort applied by the scrapers and other equipment. Each particle size will react somewhat differently than another under the same pressure and water content. Therefore, the same compactive effort will not have the same effect on the various particle sizes.

One other point should be noted about the cone index data discussed above. Initial tillage treatments were applied in the fall of 1987 and each location had a light disking operation prior to the reseeding operation in the spring of 1989. The first penetrometer readings were not taken until the spring of 1990 due to construction delays in obtaining several components of the penetrometer that were backlogged at the supplier. Thus over 2.5 years had passed between the initial tillage treatments and the initial penetrometer measurements were made. This time lapse most likely contributed to the general lack of significant differences in cone index values among tillage treatments. Differences may have been detected had the equipment been available in

1988. This would also have given a much more precise change in cone index values with time following the tillage treatments. This does not, however, detract from the differences found within the deep-rip topsoil tillage shank track data which are still present at the locations from the fact that mean location soil strength within the entire profile is still increasing due, mainly, to increasing bulk density values and decreasing soil water contents (discussed below).

3. Soil Water

Mean estimated available soil water by depth at the two locations is shown in Fig. 7. During most years, the upper soil profile was in a deficit situation at one time or another at both locations. As explained earlier this was due to below long-term average rainfall amounts in addition to forage use. Some overwinter/spring soil water recharge did occur at both locations. After 1989, subsoil soil water values were deficient by midsummer although some fall recharge occurred at the Center location in 1991.

Deep subsoil available soil water (0.6 to 1.2 m depth) was virtually nonexistent at the Coteau location in 1990 and 1991. Amounts at the Center location showed an almost steady decrease with time until essentially no available soil water was present by late 1992.

As expected, the greatest variation in the data was in the upper profile (0 to 0.3 m). This was due to rainfall, spring snowmelt, and forage use.

4. Yields

Few significant tillage treatment effects on forage yields for either within years or with time were found at these two locations (Table 16). Differences for within and between the deep-rip topsoil tillage treatment shank tracks were also, for the most part, nonsignificant. Actual yields for the locations are listed in Appendix Tables A13-A15.

Forage yields at these two locations were heavily influenced by growing conditions within the years. As discussed earlier, less than normal rainfall with generally above normal temperatures and low amounts of stored available soil water led to stressful growing conditions. Also, because hot, droughty conditions in 1988 resulted in very poor stands at both locations, the plots were reseeded in 1989 nearly 18 months after the tillage treatments had been applied. Vegetative stands, even after the reseeding operation, were not uniform because of the growing conditions in 1989. This also affected the yields by increasing the variability of the data.

Mean location yields did increase from 1990 to 1991 at both locations as the forages became better established and early-season growing conditions improved sightly. Forage yields at the Center location decreased significantly from 1991 to 1992 due to early hot, dry growing conditions. Yields were taken about 2 to 3 weeks earlier than in 1990 and 1991 because of leaf sloughing on the alfalfa.

Each year following the yield measurements, the remainder of the forages were removed by farmer-cooperators or mining personnel. Regrowth from harvest to fall freeze-up in 1990 and 1991 was minimal. Alfalfa regrowth was generally less than 30 cm as was the case for the grasses. In 1992 at Center, however, growing conditions improved after the first harvest. Temperatures moderated, rainfall came more frequently than normal though still mostly in daily amounts less than 1 cm, and increased cloudiness reduced evapotranspirative demand. This resulted in the farmer-cooperator at Center actually getting a second harvest from that location that looked to be better than the first harvest (no actual measurements were made). This was the only second harvest performed on the location over the time period covered in this report.

5. Roots

Rooting depths of the alfalfa at the Center and Coteau locations has progressed to over 1 m since 1989, this in spite of the somewhat adverse growing conditions that the alfalfa has had to endure. This progression can be seen in Figs. 8 and 9.

Root-length density measurements showed few significant tillage effects within any of the years of data for either location (Appendix Tables A16 and A17). No tillage treatment, either topsoil or subsoil, had consistently higher values than the others. However, the data does seem to indicate that the no till subsoil tillage treatment is restricting root penetration at depths where roots are present in the other treatments. This was especially evident at the Center location in 1992.

Root mass data (approximate soil volume of 425 cc) at the two locations (Appendix Tables A18 and A19) had similar results as found for the root-length density data. Root mass has increased for most depth intervals from one year to the next but no treatment seems to be the best within any one year consistently for the entire profile.

Tables 17 and 18 show that differences also existed between the two locations as to what factors affected, with time, root-length density and root mass. Some of this was attributed to an additional year of data from the Center location where differences between treatments are generally decreasing. Also, as time progressed, it was more difficult to obtain alfalfa root samples that were not contaminated with roots from the grasses that were growing with the alfalfa.

Yearly differences were expected to be significant since root growth would continue to expand with time. As noted earlier, year effects at deeper depths appeared as rooting growth continued.

Since few significant differences for the various profile depth increments as a result of tillage were found for bulk density or cone index, the lack of differences in the root data was consistent. High variability in the data within and between years was also a cause of the lack of differences. Even within any one topsoil by subsoil tillage treatment, variability in depth of rooting and the above two factors was high. This effect was in addition to the above-mentioned effect of contamination by grass roots.

These problems in data variability from one year to the next can be readily seen by comparing Appendix Tables A17 and A19 for the 1990 and 1991 data at Coteau. While root-length density decreased for all subsoil tillage treatments, root mass increased in the 15 to 30 cm depth increment. While the increase in mass was expected, the decrease in root-length density was not expected. It was postulated that maybe some sloughing of secondary roots on the alfalfa occurred or fewer grass roots were in the 1991 data.

As was the case for the cone index values, it is assumed that some significant differences in these rooting factors may have been found if the locations did not need to be reseeded in 1989. Root growth would have had an earlier opportunity to penetrate the soil materials prior to some of the reconsolidation which occurred and resulted in higher bulk density and cone index values. On the other hand, earlier growth would have depleted stored soil water reserves more quickly which may have slowed down deeper rooting by the alfalfa.

To the extent to which this research was completed, the measured bulk densities and cone index values found haven't as yet affected downward root penetration in the soil. The lack of roots penetrating the no till subsoil treatment at Center may be due to a thin, highly compacted layer that is not readily seen by the depth increments used in this experiment for bulk density or cone index. It is also possible that this is an effect of low available soil water or surface growing conditions (weather).

Correlation/regression analyses were performed on the root-length density data to determine if bulk density or cone index was a better estimator. Only the last year of data at each location (1992 for Center and 1991 for Coteau) was used with only those depth increments containing roots included in the data set.

Coefficients of determination for both linear and quadratic equations are listed in Table 19. Near surface values were poor due to such factors as contamination of samples by grass roots and high variability in the data. Values generally increased with depth due to somewhat less variability in the data except at Coteau (no apparent cause could be readily determined). For the majority of these depths, cone index was as good as or better than bulk density for determining root-length density. Since this methodology should approximate to a better extent what a growing root would encounter than bulk density would, the data from these two locations seems to agree.

B. Topsoil Tillage/Forage Locations

1. Bulk Density

Mean soil bulk densities were obtained in 1989 during access tube installation at the Glenharold and Knife River locations (Tables A20 and A21, respectively). Treatment effects on bulk densities removed in 0.3 m core increments were significant for only one depth only at the Knife River location (Table 20). This significant tillage effect was attributed to variability across the location since the effect was found for a depth deeper than the applied tillage treatments. Bulk densities from the subsoiled areas were generally lower than from the chisel treatments, but the variations in soil reconstruction and sampling variability across the tillage locations generally led to no significant differences. Compacted soil layers remained in the subsoil treatments since the tillage action of the subsoiler was to follow weaknesses in the reclaimed soil. Total dissipation of those tillage strips was not achieved.

Table 21 shows least significant differences by years among bulk densities obtained during the length of study from the topsoil tillage locations (see Tables A22 and A23). Results follow those from Table 20 in that almost no significant differences occurred in any year among bulk density values. The significant differences in 1991 at Glenharold were only just barely significant. Those differences in 1992 at Knife River which occurred below the depth of subsoil tillage (0.6 m) were caused by sampling variability. Samples were not taken directly from the subsoil shank tracks at either location in order to diminish bias. Samples were instead taken at random across tillage plots to obtain mean conditions.

When bulk densities by depth were averaged over crops, few significant tillage treatment differences were found in the yearly data at either location (Fig 10). Variability in the data from the soil core samples determined to a large extent the presence or absence of significance. This variability over the entire plots again resulted in some significant differences between tillage treatments below the depth of tillage.

At both tillage locations, soil bulk densities have been variable with time (see Tables A22 and A23). Results from the study indicated some decrease in bulk densities with time, especially with higher soil moisture conditions (Fig. 11). This result may indicate that if the soils become moist and remain that way for several years, soil bulk densities may stabilize or become smaller due to freezing action, chemical bonding of soil particles and biotic activity. Compacted soil layers will remain until sufficient water can again enter the soil.

2. Soil Strength

Penetrometer work at the Glenharold and Knife River locations has shown that subsoiling has maintained lower cone index values than chiseling during the length of study to 0.6 m which was the depth of the subsoil tillage (Tables A24 and A25). Figures 12 and 13 show the results of the three years of cone penetrometer data from Glenharold and Knife River, respectively. The most dramatic results of subsoiling are at Glenharold where soil penetration resistance was reduced about 50% in the upper 0.6 m of soil. A prominent cone index maximum occurred at 0.2 m at Knife River due most likely to surface tillage, traffic, and planting operations.

The lower penetration resistance from the subsoil tillage treatment coincides with the lower bulk densities from the same treatment. However, the maximum cone indices which occurred near the surface at Knife River (see Figure 13) do not indicate the presence of greater bulk densities. One reason for this result is that, often, bulk densities are calculated using 0.15 to 0.3 m long soil cores which temper bulk density values over any compaction layers. An attempt in 1990 to take smaller soil cores for correlation with penetrometer cone indices resulted in widely diverse bulk density values in adjacent soil layers caused by the difficulty of sectioning hard soils precisely enough for accurate bulk density determinations.

Tables 22 and 23 show least significant differences among mean penetrometer cone indices from the Glenharold and Knife River locations, respectively. The significant differences in the Year and Tillage effects were not surprising given the fact that the soils have become firmer during the past three years, and that the subsoil treatments have shown consistently lower soil strengths to the depth of subsoil tillage (0.6 m). The significant differences at 0.85 m was due mostly to sampling variation.

Significant cone index differences also occurred among main effects involving crops (see Tables A24 and A25). Figure 14 shows mean cone indices for all crops from the two tillage locations. Mean cone indices by crop from Glenharold follow similar patterns, with the small grain subplots having the lowest values. Cone indices from Knife River showed significantly lower values from the small grain treatments at most depths. It is not clear why these subplots had lower cone indices, however, these were the only subplots tilled annually. Perhaps the greater surface aeration allowed for greater water percolation and biotic activity. Greater root proliferation, then decay, during each growing season may also have produced a looser soil to a soil depth of 0.7 m at Knife River.

Table 24 presents regressions of cone indices to soil physical parameters from the Glenharold and Knife River locations. The better regression occurred at Glenharold as evidenced by the larger coefficient of multiple determination. The Glenharold regression was better because the pattern of cone indices with depth did not have a prominent maximum at 0.2 m depth as at Knife River. As explained earlier, this maximum did not necessarily indicate an increased bulk density as measured from soil cores due to physical soil core size constraints. However, both regressions showed appropriate coefficients on the main soil parameters, increased cone indices with increased bulk density and decreased cone indices with increased gravimetric water content.

3. Soil Water

The past four years have seen continued shortages in soil water quantity at the topsoil tillage locations. Figures 15 and 16 show mean available soil water averaged over crops by soil layers from the beginning to the end of each growing season at the Glenharold and Knife River locations, respectively. Sporadic, often light, rains and high growing-season temperatures the first two years led to a dramatic drawdown of soil water in the upper 0.9 m of soil at Knife River and in the upper 0.6 m of soil at Glenharold. The years 1991 and 1992 showed much improved soil water status during spring at both locations, but only to soil depths of about 0.6 m. Soil layers below 0.6 m showed little change in soil water depth the last two years of the study. Growing-season rainfall during the study period was often only sufficient to wet the upper 0.6 m of soil.

Soil water within the soil profiles, by tillage treatments, was similar within locations. Greater total available soil water amounts were found in the subsoil treatments at Glenharold, while the chisel treatments had slightly more water at Knife River. With the lower bulk densities in the subsoil treatments, it could have been expected that greater depths of soil water would be found for this treatment. Certain factors could explain the absence of this effect. Water may have continued to drain or evaporate from the subsoiled sandy loam soil at Knife River. The higher clay content of subsoil and spoil at Glenharold prevented such movements even though bulk densities were lower (porosity higher) than at Knife River. Another factor could be that increased preferential flow of water occurred along access tubes in the lower bulk density soil at Glenharold. The soil at Knife River may have become somewhat consolidated which may have reduced preferential flow near access tubes.

Overall, soil water conditions remained dry throughout most of the study period. Beneficial, timely rains which did not improve measured soil water amounts deeper than 0.6 m did, however, improve crop prospects and yields in many instances (discussed later).

4. Yields

Small grain (wheat) yields were taken from both tillage locations each year (Table A26). Yearly mean yield differences were significant at both locations (Table 25). However, only Knife River had overall significant mean yield differences between tillage treatments and among all mean yields sampled during the length of study (Year x Tillage). Most of the significant yield differences due to tillage at the Knife River location occurred because in 1989 the subsoil treatment out yielded the chisel treatment by nearly 400% (Table A26). In 1989 at Knife River, about 50 mm of rain fell onto the newly tilled plot and apparently percolated deeply within the subsoiled treatments. The rest of the 1989 growing season was dry, and final wheat yields presented in Table A26 occurred as a result. Table 26 shows the yearly least significant differences for wheat yields between tillage treatments for the two locations. Differences which occurred in 1991 at Knife River and in 1992 at Glenharold were most likely caused by differences in fertility (discussed later), by some noted differences in available water at planting, or by sampling variability.

Wheat yields obtained in 1992 following the conversion of the tillage location to evaluate prior cropping effects are given in Table A27. Least significant yield differences from the converted plots are shown in Table 27. Both locations had significant yield differences due to prior cropping. Knife River also showed a significant yield difference in Tillage x Prior Crop. The greatest yields occurred in the prior native mix strips at Glenharold and the prior small grain strips at Knife River (see Table A27). The wheat yields at Knife River were not surprising since residual fertility in the small grain strips at the time of plot conversion was greater than in any other strips (Table 28). Some of the decrease in yields was attributed to the reseeding that occurred only at this location. However, the native mix strips at Glenharold had the lowest residual fertility. They were not fertilized any heavier than the other strips in April, 1992, yet they yielded the greatest amount of wheat by August, 1992. Perhaps the native plants decayed the fastest and delivered more nitrogen to the wheat than the other forages, or greater amounts of water were able to penetrate the native mix plots after tillage in 1991.

Table 29 shows least significant forage yield differences between the tillage treatments for the tillage locations for the years of study (see Tables A28 and A29). Data were not obtained in 1989 due to the poor plant stand and the stressed condition of the plants. Only the precrop mix in 1992 at Glenharold showed any significant difference due to tillage. These results show that weather conditions, not tillage or compaction effects were the dominant factor influencing forage yields at these two locations. This can be seen in Fig. 17 which shows, generally, a significant increase in yield from 1990 to 1991 due to better growing conditions and establishment. A significant decrease from 1991 to 1992 occurred due to (hot, dry) growing conditions in the spring.

5. Roots

Rooting characteristics of the various crops were evaluated to provide an indication of the ability of reclaimed soils to become adequate plant growth media. Reclaimed soils which support actively growing roots stand a better chance of producing sufficient crop yields which are used as a measure of reclamation success. Roots were sampled from both tillage locations during the four years of study (Tables A30, A31, A32, and A33). Root length and mass densities averaged over all crops from the Glenharold and Knife River locations are shown in Figures 18 and 19, respectively. Both locations experienced increased root length densities (RLD) and generally increased root mass densities (RMD). Rooting depths, on average, were greater at Knife River than Glenharold, most likely due to the presence of high SAR spoils at Glenharold which tend to suppress root growth.

RMD values did not change much during the last three years at either tillage location (see Figs. 18 and 19). It is possible that the increased RLDs during these drier years was due mostly to fine roots which were needed by the plants to extract water from small pores. These fine roots also do not provide a large mass even though they do provide great length. In addition, the amount of dead roots in these soils is steadily increasing, potentially adding measurement errors in terms of length while at the same time being largely uncounted in terms of mass.

Table 30 shows least significant differences among mean RLDs and RMDs by main effects from the Glenharold location. Nearly all effects at all depths showed significant rooting differences as could have been expected after examining Fig. 18. Similar results from Knife River are presented in Table 31.

In general, roots at both locations appear to have successfully permeated the entire reclaimed soil profiles (above spoil material). Anticipation for continued adequate crop yields from those soils based on these rooting characteristics, given beneficial weather conditions, should remain high.

Table 32 gives coefficients and coefficients of multiple determination of various soil physical parameters used to explain rooting characteristics from the Glenharold and Knife River locations. In all cases, penetrometer cone index and soil wet bulk density were significant parameters. Occasionally, soil gravimetric or volumetric water content would be significant, but the contribution of these parameters was minimal and, thus, were not reported. The soil parameter coefficients were all of expected sign, negative, for explaining increased root growth. The R^2 values were not substantial, indicating the difficulty of trying to explain the habits of dynamic, living objects by using basically static, inanimate physical parameters.

C. Long-Term Locations

Bulk density samples were taken from the old Falkirk trench site in 1990 to investigate how reclaimed soils have developed during an 11-year period. The old trench was established in 1979 to study crop growth on various types and depths of soil and spoil materials. Table 33 shows least significant differences of mean bulk densities taken from the trench in those two years (see Table A34). The most prevalent significant bulk density differences occurred in those main effects associated with subsoil treatments. The various subsoil materials apparently consolidated at different rates causing the large variability in subsoil bulk densities. Not even the Year main effect showed any significant differences at any depth increment suggesting only slow, if any, significant bulk density changes occurring with time at this site. Mean values are illustrated in Fig. 20.

Table 34 presents least significant bulk density differences from two sampling dates (1986 and 1992) at the Center and Falkirk topography locations (see Tables A35 and A36). The majority of significant differences occurred in the Year main effect at both locations. Bulk densities have generally increased at both locations during the interim. Some decrease was noted at the Falkirk forage area shoulder and backslope due to animal burrowing (see Table A36). The small grain area at Falkirk experienced significant increases in bulk density by position (see Table 34). The actions of machinery during annual tillage operations and possible water-enhanced illuviation at several profile depths most likely assisted soil reconsolidation at this location area. The mean changes at Center and Falkirk are illustrated in Fig. 21 and 22, respectively.

Overall, soil bulk densities have increased with time at nearly all locations and depths not drastically disturbed by burrowing animals. In many instances, these increases were not statistically significant, buy may be important since many tilled unmined agricultural soils experience bulk density increases for several years after tillage operations cease. Given time and, more importantly, soil water, these reclaimed soils should stabilize to the point at which bulk densities will cease to increase and most likely will begin to decrease.

V. CONCLUSIONS

Experiments were conducted to determine the effectiveness with time of tillage for ameliorating compaction on reclaimed minelands caused by heavy equipment during the respreading operations. From the previous discussion, several conclusions may be drawn from the data:

1. Subsoil tillage prior to topsoil respreading did not have a significant effect on resultant bulk density following topsoil respreading with scrapers. Scraper and grader traffic during topsoil respreading compacted the tilled subsoil to bulk densities equal to areas left untilled.
2. Attempts to spread subsoil with scrapers and minimum traffic to reduce compaction were also not effective. Over half of the materials were compacted due to the scraper tires during the respreading operation. Most of the remaining subsoil material was compacted during levelling by graders and topsoil respreading.
3. Bulk densities increased significantly with time in the subsoil regardless of the tillage treatment applied due to reconsolidation of soil particles and depletion of soil water. The majority of change occurred within three to four years after reclamation.
4. Bulk densities near the surface generally decreased significantly with time due to vegetative growth, wetting/drying and freeze/thaw. However, adverse weather conditions during the final year of these experiments increased bulk density to values not significantly different from those of several years earlier at some

locations. Differences among topsoil tillage treatments generally decreased with time to where bulk density values were not significantly different after about 4 y.

5. Soil strength, as measured with a cone penetrometer, showed increasing values with time as bulk density increased. Bulk density was the major contributing variable for estimating soil strength during correlation/regression analyses.

6. Evidence of the areas disturbed by the shank of the deep rip implement were still present more than four years after the tillage treatment was applied. Soil materials in the shank tracks had not reconsolidated as much as between the shank tracks as measured by the cone penetrometer. This suggests that close spacing of shanks on this type of implement may be effective in maintaining lower soil strength with time for potentially greater rooting depth and water infiltration.

7. Low available soil water negatively affected vegetative growth and, as amounts decreased with time, bulk densities. Soil water amounts were not sufficient below the near-surface areas to significantly decrease bulk densities during freeze/thaw cycles.

8. Yields at all locations were adversely affected by low amounts of stored available soil water amounts, below normal growing-season rainfall, and generally hot summer temperatures. These factors also affected the initial germination of the planted forages resulting in either reseeding and/or plants entering the winter season under stress.

9. Rooting depth, root length density, and root mass values for the various forages measured have increased with time. However, few significant tillage effects were

found. Overall mean values for bulk density and soil strength at the sites by depth have not, as yet, reached values where root penetration (except in small areas) has been stopped completely. Growth to deeper depths may slow down because of small amounts of available soil water.

10. Wheat yields at the topsoil tillage/forage locations showed little effect from tillage. The only major difference occurred the first year of study at one location as a result of a heavy rain immediately following application of the tillage treatments. Soil water contents presumably increased markedly at depth in the subsoil tillage treatment, but not so in the chisel treatment. Resultant wheat yields from the subsoil treatment after a growing season of below normal rainfall, showed nearly a 400% increase over yields from the chisel treatment. This result was an isolated case not likely to be repeated with any regularity.

11. Wheat yields from prior-cropped strips were inconsistent. The prior-cropped strips affected yields at the two topsoil tillage/forage locations differently. However, yield differences among prior-crops were significant at both locations. No definite reasons for the observed results have been reached although some of the difference was attributed to available soil water at planting.

12. Bulk densities from long-term locations indicate that trends towards higher bulk densities in subsoils and lower bulk densities near the surface with time (up to 11 years) in reclaimed soils can be expected. Maximum subsoil bulk densities have most likely been reached at one location, and may be approaching a maximum at the other two locations. The outlook for other reclaimed minesoils is similar

given a return to more normal weather conditions within the current climatic pattern.

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TABLES 1-34

Table 1. Tillage characteristics for the Center study site (fall, 1987) following grading to level the surface.

Tillage	Average Spacing	Depth Range	Average Depth
		(cm)	
		Topsoil Treatments	
Chisel	30	13-18	15
Deep Rip†	127	102-122	114
Grader Rip‡	137	25-36	30
		Subsoil Treatments	
Chisel	30	10-18	15
Deep Rip†	122	122-135	127
Grader Rip‡	137	20-33	28
Deep Lift§	---	----	---
No Till	---	----	---

†Completed with a D9 bulldozer with a 13 cm thick shank.
‡Standard grader with 8 cm thick shanks.
§Respread as deep as possible with minimal traffic.

Table 2. Tillage characteristics for the Coteau study site (fall, 1987) following grading to level the surface.

Tillage	Average Spacing	Depth Range	Average Depth
		(cm)	
		Topsoil Treatments	
Chisel	30	10-18	15
Deep Rip†	107	48-64	58
Grader Rip‡	68	30-51	43
		Subsoil Treatments	
Chisel	30	10-18	15
Deep Rip†	107	61-76	64
Grader Rip‡	68	30-36	33
Deep Lift§	---	----	---
No Till	---	----	---

†Large subsoiler with 4 cm thick shanks.
‡Standard grader with 8 cm thick shanks.
§Respread as deep as possible with minimal traffic.

Table 3. Tillage characteristics from the Glenharold and Knife River topsoil tillage locations, spring 1989.

Tillage	Depth	Spacing
	(m)	
Chisel	0.15	0.30
Subsoil	0.60	0.52

Table 4. Seeding rates of plant materials used at the experiment locations.

Material	Center	Coteau	Glenharold	Knife River
		(kg ha^{-1})		
Alfalfa (*Medicago sativa*)	4.9	4.9	11.2	11.2
Native Mix			20.2	20.2
Sideoats grama (*Boutelova curtipendula*) 33%				
Green needle (*Stipa viudula*) 19%				
Big bluestem (*Audropogon gerardii*) 17%				
Western wheatgrass (*Pascopyrum smithii*) 14%				
Blue grama (*Bouteloua gracilis*) 11%				
Slender wheatgrass (*Elymus trachycaulus*) 6%				
Precrop Mix			16.8	16.8
Alfalfa 33%				
Pubescent wheatgrass (*Thimopyrum intermedium*) 27%				
Tall wheatgrass (*Thimopyrum pontium*) 20%				
Smooth brome (*Bromus inermis*) 20%				
Pubescent wheatgrass	4.9	4.9	9.0	11.2
Tall wheatgrass			9.0	11.2
Spring wheat (*Tritrium aestivum*)			84.0	84.0
Western wheatgrass	4.4	4.4		
Oats (*Avena satium*) as cover crop	11.2	11.2		

Table 5. Precipitation measured at or near the tillage plot locations.+

Dates‡	Location		
	Glenharold	Center	Knife River
		(cm)	
4/28 to 10/3/88	----	12.8	----
		(-18.8)§	
4/26 to 10/9/89	14.9++	24.0	15.9++
	(-19.4)	(-8.6)	(-16.2)
4/19 to 10/29/90	31.7	33.8	29.6
	(-5.4)	(-2.0)	(-4.2)
4/10 to 10/28/91	29.0	35.1	25.0
	(-6.7)	(-0.4)	(-10.0)
4/14 to 10/19/92	22.5	21.6	18.9
	(-13.5)	(-13.8)	(-14.9)

+No rain gauge in the Coteau location vicinity. At Center the rain gauge was approximately 1.5 km from the location.

‡Rain gauges were generally installed at small grain planting and removed prior to daytime temperatures remaining below freezing.

§Deviation from long-term average using NOAA data for the time period listed.

++Rain gauges installed May 25.

Table 6. Mean dry bulk densities from access tube installation cores for the Center tillage study location (fall, 1987)

Tillage Treatment[+] Topsoil	Subsoil	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
						(g/cm³)					
						Topsoil Treatment[+]					
CHIS		1.26	1.42	1.58	1.64	1.62	1.52	1.53	1.57	1.70	1.74
DR		1.15	1.36	1.42	1.60	1.60	1.55	1.47	1.55	1.62	1.65
GR		1.30	1.36	1.55	1.65	1.68	1.57	1.59	1.59	1.66	1.72
LSD(0.10)[§]		0.06	NS	0.06	NS	0.05	NS	0.08	NS	NS	NS
						Subsoil Treatment[+]					
	CHIS	1.22	1.36	1.53	1.61	1.61	1.58	1.53	1.58	1.70	1.69
	DL	1.34	1.40	1.49	1.63	1.65	1.46	1.54	1.57	1.56	1.67
	DR	1.18	1.39	1.51	1.62	1.63	1.57	1.51	1.58	1.66	1.74
	GR	1.17	1.35	1.51	1.62	1.61	1.53	1.48	1.52	1.69	1.76
	NT	1.28	1.39	1.54	1.68	1.67	1.60	1.58	1.58	1.68	1.67
LSD(0.10)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
						Topsoil x Subsoil Treatment[+]					
CHIS	CHIS	1.18	1.39	1.57	1.59	1.57	1.62	1.60	1.59	1.69	1.68
	DL	1.34	1.43	1.52	1.66	1.60	1.26	1.48	1.56	1.64	1.78
	DR	1.31	1.43	1.56	1.70	1.66	1.59	1.49	1.58	1.67	1.71
	GR	1.26	1.41	1.64	1.61	1.59	1.52	1.48	1.50	1.73	1.80
	NT	1.23	1.43	1.62	1.67	1.70	1.60	1.59	1.61	1.74	1.76
DR	CHIS	1.21	1.35	1.43	1.55	1.56	1.46	1.36	1.49	1.70	1.67
	DL	1.35	1.36	1.39	1.58	1.60	1.60	1.54	1.51	1.44	1.53
	DR	1.00	1.39	1.41	1.60	1.60	1.53	1.46	1.58	1.64	1.80
	GR	1.10	1.34	1.42	1.63	1.59	1.52	1.41	1.53	1.68	1.71
	NT	1.11	1.33	1.46	1.64	1.66	1.64	1.58	1.62	1.63	1.53
GR	CHIS	1.26	1.35	1.59	1.68	1.69	1.65	1.62	1.68	1.71	1.71
	DL	1.34	1.42	1.56	1.65	1.75	1.52	1.62	1.65	1.60	1.69
	DR	1.23	1.34	1.56	1.56	1.63	1.56	1.60	1.58	1.69	1.72
	GR	1.16	1.30	1.47	1.64	1.65	1.56	1.55	1.52	1.66	1.77
	NT	1.49	1.40	1.54	1.72	1.66	1.56	1.59	1.51	1.65	1.71
LSD(O.10)		0.14	NS	NS	NS	NS	0.16	NS	NS	NS	NS

Depth (cm) spans columns 0-15 through 135-150.

[+]CHIS = chiselled, DR = deep ripped (D9 bulldozer), GR = grader ripped, DL = deep lift replacement, and NT = no tillage.
[+]15 replications for topsoil, 9 for subsoil, 3 for topsoil x subsoil.
[§]Least significant difference at the 10% level. NS indicates no significant differences between values.

Table 7. Mean dry bulk densities from access tube installation cores for the Coteau tillage study location (fall, 1987)

Tillage Treatment[†]		Depth (cm)									
Topsoil	Subsoil	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
							(g/cm³)				
							Topsoil Treatment[‡]				
CHIS		1.17	1.32	1.47	1.49	1.53	1.49	1.50	1.49	1.54	1.57
DR		1.13	1.31	1.42	1.48	1.51	1.49	1.52	1.49	1.51	1.55
GR		1.25	1.43	1.45	1.51	1.48	1.50	1.48	1.52	1.54	1.56
LSD(0.10)[§]		NS	0.10	NS	NS	NS	NS	NS	NS	NS	NS
							Subsoil Treatment[‡]				
	CHIS	1.19	1.31	1.40	1.45	1.47	1.44	1.47	1.53	1.54	1.59
	DL	1.25	1.38	1.52	1.53	1.47	1.46	1.48	1.47	1.51	1.58
	DR	1.12	1.36	1.45	1.54	1.51	1.48	1.52	1.50	1.56	1.55
	GR	1.13	1.38	1.44	1.46	1.52	1.49	1.47	1.44	1.51	1.55
	NT	1.23	1.36	1.43	1.48	1.56	1.58	1.56	1.55	1.52	1.53
LSD(0.10)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
							Topsoil x Subsoil Treatment[‡]				
CHIS	CHIS	1.23	1.36	1.47	1.47	1.51	1.46	1.46	1.52	1.58	1.60
	DL	1.18	1.24	1.52	1.54	1.47	1.46	1.45	1.51	1.49	1.62
	DR	1.19	1.32	1.52	1.53	1.54	1.54	1.52	1.43	1.58	1.53
	GR	1.01	1.31	1.46	1.48	1.55	1.42	1.48	1.43	1.49	1.58
	NT	1.23	1.34	1.39	1.43	1.57	1.55	1.56	1.54	1.55	1.51
DR	CHIS	1.04	1.24	1.34	1.39	1.43	1.44	1.50	1.52	1.47	1.59
	DL	1.30	1.40	1.48	1.48	1.45	1.52	1.48	1.45	1.52	1.52
	DR	1.05	1.31	1.40	1.55	1.56	1.43	1.57	1.48	1.53	1.49
	GR	1.17	1.36	1.41	1.47	1.48	1.50	1.47	1.46	1.54	1.58
	NT	1.10	1.27	1.48	1.52	1.62	1.55	1.60	1.55	1.48	1.55
GR	CHIS	1.28	1.32	1.38	1.49	1.45	1.43	1.46	1.56	1.58	1.58
	DL	1.27	1.49	1.57	1.58	1.51	1.40	1.49	1.45	1.51	1.58
	DR	1.13	1.43	1.42	1.54	1.43	1.50	1.48	1.60	1.58	1.64
	GR	1.20	1.46	1.46	1.45	1.53	1.53	1.47	1.44	1.50	1.48
	NT	1.35	1.46	1.42	1.51	1.50	1.63	1.51	1.57	1.52	1.53
LSD(O.10)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[†]CHIS = chiselled, DR = deep ripped (subsoiler), GR = grader ripped, DL = deep lift replacement, and NT = no tillage.

[‡]15 replications for topsoil, 9 for subsoil, 3 for topsoil x subsoil.

[§]Least significant difference at the 10% level. NS indicates no significant differences between values.

Table 8. ANOVA significance summaries by sampling date for bulk density from soil coring at the Center tillage location.

Anova Variable	Year of Data[†]							
	1987C	1989R	1990P	1990R	1991P	1991R	1992P	1992R
				Depth: 0-0.3 m				
Topsoil Tillage (Top)		*[‡]			***			
Subsoil Tillage (Sub)	**			***				**
Top x Sub	**	***						
				Depth: 0.3-0.6 m				
Top	***	*		*	*		***	
Sub	***			***	**	**		
Top x Sub		**						*
				Depth: 0.6-0.9 m				
Top		ND[δ]	ND			**		
Sub		ND	ND		*			
Top x Sub		ND	ND			**	**	
				Depth: 0.9-1.2 m				
Top		ND	ND			ND	***	
Sub		ND	ND		**	ND		
Top x Sub		ND	ND			ND		

[†]C = access tube installation, P = penetrometer cores, and R = root cores.

[‡]*, **, and *** indicate significance at the P = 0.01, 0.05, and 0.10 levels, respectively. Blanks indicate levels greater than P = 0.10.

[δ]No data or insufficient data for analysis.

Table 9. ANOVA significance summaries by sampling date for bulk density from soil coring at the Coteau tillage location.

ANOVA Variable	Year of Data+					
	1987C	1989R	1990P	1990R	1991P	1991R
			Depth: 0-0.3m			
Topsoil Tillage (Top)	**‡	***		**		
Subsoil Tillage (Sub)						
Top x Sub						
			Depth: 0.3-0.6m			
Top	**					
Sub					**	
Top x Sub	**					
			Depth: 0.6-0.9m			
Top	***	ND[δ]				
Sub		ND			*	
Top x Sub		ND				***
			Depth: 0.9-1.2m			
Top		ND				ND
Sub	***	ND			*	ND
Top x Sub		ND				ND

+C = access tube installation, P = penetrometer cores (spring), and R = root cores (fall).

‡*, **, and *** indicate significant at the P = 0.10, 0.05, and 0.10 levels, respectively. Blanks indicate levels greater than P = 0.10.

δNo data or insufficient data for analysis.

Table 10. ANOVA summaries with time for core bulk density values at the Center and Coteau locations.

ANOVA Variable	Profile Depth (m) 0-0.3	0.3-0.6	0.6-0.9	0.9-1.2
		Center Location +		
Year of Data (Yr)	*+	*	*	*
Topsoil Tillage (Top)	*	*	*	**
Subsoil Tillage (Sub)	*	*	*	*
Yr x Top			**	**
Yr x Sub			**	
Top x Sub		**	*	**
Yr x Top x Sub		**	**	**
		Coteau Location +		
Yr	*	***	*	**
Top	**		***	
Sub	*	**	*	*
Yr x Top	**		***	
Yr x Sub	*	*	*	*
Top x Sub				
Yr x Top x Sub				

+*, **, and *** indicate significance at the P = 0.01, 0.05, and 0.10 levels, respectively. Blanks indicate levels greater than P = 0.10.

+Data from 1987 through 1992 for Center, 1987 through 1991 for Coteau.

Table 11. ANOVA significance summaries by year and tillage depths for mean cone index values at the Center and Coteau locations.

ANOVA Variable	Profile Depth (cm) 0-15	15-30	30-35	35-50	50-65	65-100	0-20	20-100	
			Center Location				Deep Rip Plots†		
					1990				
Topsoil Tillage (Top)			**†	*		ND[§]		**	
Subsoil Tillage (Sub)	***	***	***			ND			
Top x Sub						ND			
					1991				
Top	***	**	*	*				*	
Sub	***								
Top x Sub								*	
					1992				
Top		**	*	**				*	
Sub				*					
Top x Sub									
	Profile Depth (cm) 0-15	15-40	40-56	56-73	73-85	85-100	0-20	20-60	60-100
			Coteau Location				Deep Rip Plots		
					1990				
Top		*				*		*	
Sub						***			
Top x Sub						**			
					1991				
Top		*						**	
Sub		***	**						
Top x Sub					***				

†Comparison of between and within shank tracks of this topsoil tillage treatment only.

‡*, **, and *** indicate significance at the P = 0.01, 0.05, and 0.10 levels, respectively. Blanks indicate levels greater than P = 0.10.

§No data or insufficient data for analysis.

Table 12. ANOVA significance summaries for cone index values by tillage depth over years at the Center tillage location.

ANOVA Factor	Profile Depth (cm) 0-15	15-30	30-35	35-50	50-65	65-100
Year (Yr)	*[+]	**	***	*	***	
Subsoil Tillage (Sub)				*	***	
Topsoil Tillage (Top)		*	*	*		
Yr x Sub				*		
Top x Sub		***				
Yr x Top					***	
Yr x Top x Sub						

Deep Rip Topsoil Plots Only[+]

Profile Depth (cm)

ANOVA Factor	0-20	20-100
Yr	*	*
Sub		
Top		*
Yr x Sub		
Top x Sub		**
Yr x Top		*
Yr x Top x Sub		

[+]*, **, and *** indicate significance at the P = 0.01, 0.05, and 0.10 levels, respectively. Blanks indicate significance levels greater than P = 0.10.

[+]Comparison of within versus between shank tracks.

Table 13. ANOVA significance summaries for cone index values by tillage depth over years at the Coteau tillage location.

	Profile Depth (cm)					
ANOVA Factor	**0-15**	**15-40**	**40-56**	**56-73**	**73-85**	**85-100**
Year (Yr)	**+	**	**	*	***	**
Subsoil Tillage (Sub)			**			
Topsoil Tillage (Top)		*				
Yr x Sub						
Top x Sub					***	
Yr x Top						
Yr x Top x Sub						

Deep Rip Topsoil Plots Only[+]

	Profile Depth (cm)		
	0-20	**20-60**	**60-100**
Yr	*	**	**
Sub			
Top		*	
Yr x Sub			
Top x Sub			
Yr x Top			
Yr x Top x Sub			

+*, **, and *** indicate significance at the P = 0.01, 0.05, and 0.10 levels, respectively. Blanks indicate significance levels greater than P = 0.10.

[+]Comparison of within versus between shank tracks.

Table 14. Correlation/regression analyses of mean cone index values for topsoil and subsoil over years at Center and Coteau.†

Topsoil‡			Subsoil§		
Variable		Coefficient	Variable		Coefficient
		Center Location			
Intercept		- 6.02	Intercept††		- 4.51
DBD		55.90	DBD		11.82
WBD		-44.76	CLAY		- 0.29
	N = 238			N = 311	
	R^2 = 0.26			R^2 = 0.16	
		Coteau Location			
Intercept		-17.32	Intercept		7.84
DBD		28.88	DBD		4.32
VFS		0.79	GRAVPC		- 0.20
CLAY		0.43	SILT		- 0.11
WBD		-23.09			
	N = 180			N = 348	
	R^2 = 0.41			R^2 = 0.10	
		Combined Locations			
Intercept		- 9.80	Intercept		- 6.33
DBD		83.23	DBD		16.80
WBD		-70.77	WBD		- 8.47
GRAVPC		- 0.62	SAND		0.07
	N = 418			N = 659	
	R^2 = 0.36			R^2 = 0.14	

†Mean values for 15 cm segments. Model form: Cone Index (MPa) = ax+...+ intercept. Unless otherwise noted, all variables are significant at the P = 0.10 level.

‡0 to 30 cm depth.

§30 to 105 cm depth.

*DBD = dry bulk density, WBD = wet bulk density, VFS = % very fine sand, CLAY = % clay, GRAVPC = % gravimetric soil water, SILT = % silt, and SAND = % sand.

††Variable not significant at the P = 0.10 level.

Table 15. Correlation/regression analyses of mean cone index values to physical parameters at the tillage locations.[†]

Location					
Center		Coteau		Combined Locations	
Variable[‡]	Coefficient	Variable	Coefficient	Variable	Coefficient
		1990 Data			
Intercept[§]	- 0.66	Intercept	23.47	Intercept	23.06
DBD	5.92	DBD	5.94	DBD	5.99
VFSSILT	- 0.07	GRAVPC	- 0.17	GRAVPC	- 0.20
		VFS	0.24	SAND	- 0.24
		SAND	- 0.26	SILT	- 0.40
N = 174		SILT	- 0.45	N = 412	
R^2 = 0.29		N = 238		R^2 = 0.49	
		R^2 = -0.66			
		1991 Data			
Intercept	-13.62	Intercept	39.02	Intercept[§]	6.28
DBD	17.38	DBD	6.27	DBD	88.34
VFSSILT	- 0.09	GRAVPC	- 0.19	GRAVPC	-0.92
N = 217		VFSSILT	0.25	SAND	- 0.17
R^2 = 0.63		SAND	- 0.39	SILT	- 0.40
		SILT	- 0.91	WBD	-71.48
		N = 290		N = 507	
		R^2 = 0.51		R^2 = 0.53	
		1992 Data			
Intercept	-15.54				
DBD	14.77				
GRAVPC	- 0.50	No Data		Same as Center	
SAND	0.11				
N = 158					
R^2 = 0.59					
		Over Years			
Intercept[§]	- 0.69	Intercept	37.48	Intercept	15.20
DBD	10.84	DBD	5.27	DBD	9.71
GRAVPC	- 0.25	GRAVPC	- 0.28	SAND	- 0.16
VFSSILT	- 0.13	VFSSILT	0.20	SILT	- 0.38
		SAND	- 0.36	VOLPC	- 0.16
		SILT	- 0.80		
N = 549		N = 528		N = 1077	
R^2 = 0.42		R^2 = 0.51		R^2 = 0.44	

[†]Using mean values for 15 cm segments to 105 cm. Equation form: Cone Index (MPa) = ax+...+ intercept.

[‡]DBD = dry bulk density (g/cm^3), VFSSILT = % very fine sand + % silt, GRAVPC = % gravimetric moisture, VOLPC = % volumetric moisture, VFS = % very fine sand, SAND = % sand, and SILT = % silt.

[§]Variable not significant at the P = 0.10 level.

Table 16. ANOVA significance summaries for forage yields at both tillage locations.

ANOVA Factor	Year of Data†						Over Years	
	1990	DR 1990	1991	DR 1991	1992	DR 1992	ALL	DR
				Center Location				
Subsoil Tillage (Sub)		*‡				*		*
Topsoil Tillage (Top)			***				**	
Sub x Top			***				*	*
Year (Yr)							*	*
Yr x Sub								**
Yr x Top								
Yr x Sub x Top								
				Coteau Location				
Sub	**				ND§	ND	**	
Top		**			ND	ND		*
Sub x Top		**			ND	ND		**
Yr							**	
Yr x Sub							**	***
Yr x Top								
Yr x Sub x Top								

†DR indicates comparisons within deep rip topsoil tillage treatment for differences between and within shank tracks. DRSH data not included in other data.

‡*, **, and *** indicate significance at the P = 0.01, 0.05, and 0.10 levels, respectively. Blanks indicate significance levels greater than P = 0.10.

§No data for this location for this year.

Table 17. ANOVA summary with time for alfalfa root length density at the two topsoil/subsoil tillage locations.

ANOVA Factor	Profile Depth (cm)							
	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120
				Center Location				
Year (Yr)	*+	*	*			***	*	*
Subsoil Tillage (Sub)	***				**	***		
Topsoil Tillage (Top)								
Yr x Sub	**				**			***
Yr x Top								
Sub x Top								
Yr x Sub x Top								
				Coteau Location				
Yr	**	**	**					
Sub				**	*	**		
Top			**	*				
Yr x Sub				***	*	**		
Yr x Top	**			**				
Sub x Top		***	**					
Yr x Sub x Top			***	**				

+*, **, and *** indicate significance at the P = 0.01, 0.05, and 0.10 levels, respectively. Blanks indicate P levels greater than 0.10.

Table 18. ANOVA summary with time for alfalfa root mass at the two topsoil/subsoil tillage locations.

ANOVA Factor	Profile Depth (cm)							
	0-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120
				Center Location				
Year (Yr)	*+	*	*			***	**	**
Subsoil Tillage (Sub)	*					*		
Topsoil Tillage (Top)								
Yr x Sub	***					*		
Yr x Top								
Sub x Top		**						
Yr x Sub x Top		***						
				Coteau Location				
Yr	*	**	***		**			
Sub	**			***	*	***		
Top		**	**					
Yr x Sub	***				*			
Yr x Top								
Sub x Top		**						
Yr x Sub x Top	**							

+*, **, and *** indicate significance at the P = 0.01, 0.05, and 0.10 levels, respectively. Blanks indicate P levels greater than 0.10.

Table 19. Coefficients of determinations regressing root length density versus bulk density or mean cone index values by depth at the topsoil/subsoil tillage locations.+

		Independent Variable			
		Bulk Density		Cone Index	
Profile Depth (cm)	N+	Linear	Quadratic	Linear	Quadratic
			Center Location		
5-15	16	0.36	0.36	<0.01	0.09
15-30	15	<0.01	0.12	0.01	0.02
30-45	15	0.03	0.05	0.16	0.16
45-60	9	0.06	0.20	0.04	0.33
60-75	6	0.01	0.12	0.10	0.36
75-90	6	0.80	0.83	0.50	0.65
90-105	5	0.06	0.23	0.09	0.24
			Coteau Location		
5-15	30	0.19	0.19	<0.01	0.02
15-30	30	0.01	0.13	0.03	0.06
30-45	30	0.15	0.16	0.24	0.42
45-60	28	<0.01	<0.01	<0.01	<0.01
60-75	17	<0.01	0.03	<0.01	<0.01
75-90	4	0.88	0.99	0.26	0.72

+Using 1992 data from Center, 1991 data from Coteau.

+Number of samples in model.

Table 20. Least significant difference (P = 0.10) among mean soil bulk densities obtained from access tube installation at the Glenharold and Knife River tillage location, spring, 1989.

Main Effect	Depth (cm) 0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5
			($Mg\ m^{-3}$)		
			Glenharold		
Tillage	NS	NS	NS	NS	NS
Crop	NS	NS	NS	NS	NS
Tillage x Crop	NS	NS	NS	NS	NS
			Knife River		
Tillage	NS	NS	0.01	NS	NS
Crop	NS	NS	NS	NS	NS
Tillage x Crop	NS	NS	NS	NS	NS

NS indicates no significant difference.

Table 21. Least significant difference (P = 0.10) among mean soil bulk densities obtained during access tube installation (1989) and penetrometer measurements (1990-1992) from the Glenharold and Knife River tillage locations.

	Year			
Main Effect	**1989**	**1990**	**1991**	**1992**
		($Mg\ m^{-3}$)		
		Glenharold		
		Depth = 0.0 - 0.3 m		
Tillage	NS	NS	0.08	NS
Crop	NS	NS	NS	NS
Tillage x Crop	NS	NS	0.10	NS
		Depth = 0.3 - 0.6 m		
Tillage	NS	NS	NS	NS
Crop	NS	NS	NS	NS
Tillage x Crop	NS	0.07	NS	NS
		Depth = 0.6 - 0.9 m		
Tillage	NS	NS	NS	NS
Crop	NS	NS	NS	NS
Tillage x Crop	NS	NS	NS	NS
		Knife River		
		Depth = 0.0 - 0.3 m		
Tillage	NS	0.06	NS	NS
Crop	NS	NS	NS	NS
Tillage x Crop	NS	NS	NS	NS
		Depth = 0.3 - 0.6 m		
Tillage	NS	NS	NS	NS
Crop	NS	NS	NS	NS
Tillage x Crop	NS	NS	NS	NS
		Depth = 0.6 - 0.9 m		
Tillage	NS	NS	NS	0.02
Crop	NS	NS	NS	NS
Tillage x Crop	NS	NS	NS	0.16

NS indicates no significant difference.

Table 22. Least significant differences (P = 0.10) among mean cone indices from the Glenharold tillage location.

Main Effects	Depth (m) 0.05	0.25	0.45	0.65	0.85
Year	0.32	0.63	0.45	NS	1.09
Tillage	NS	0.57	0.91	NS	NS
Year x Tillage	NS	NS	NS	NS	NS
Crop	0.24	0.72	NS	1.11	NS
Year x Crop	0.47	1.38	2.02	NS	NS
Tillage x Crop	0.34	NS	NS	NS	NS
Year x Tillage x Crop	NS	NS	NS	NS	NS

NS indicates no significant difference.

Table 23. Least significant differences (P = 0.10) among mean cone indices from the Knife River tillage location.

Main Effects	Depth (m) 0.05	0.25	0.45	0.65	0.85
Year	0.39	NS	NS	0.97	0.93
Tillage	NS	1.29	0.82	NS	NS
Year x Tillage	NS	NS	NS	NS	NS
Crop	0.32	1.21	1.82	1.30	1.75
Year x Crop	0.61	NS	NS	NS	3.18
Tillage x Crop	NS	NS	NS	NS	NS
Year x Tillage x Crop	NS	NS	NS	NS	NS

NS indicates no significant difference.

Table 24. Results of regressions of mean cone indices to mean soil physical parameters from the Glenharold and Knife River locations.

Parameter	Coefficient	
Glenharold (n = 216)		
Intercept	- 3.63	$R^2 = 0.54$
Soil Dry Bulk Density (Mg m^{-3})	8.86	
Gravimetric Water Content (kg kg^{-1})	-30.35	
Knife River (N = 206)		
Intercept	- 5.93	$R^2 = 0.32$
Soil Dry Bulk Density (Mg m^{-3})	11.28	
Gravimetric Water Content (kg kg^{-1})	-34.25	

Table 25. Least significant differences (P = 0.10) among mean wheat yields from the Glenharold and Knife River tillage locations.

Main Effect	Glenharold	Knife River
	(Mg ha^{-1})	
Year	0.17	0.07
Tillage	NS	0.05
Year x Tillage	NS	0.11

NS indicates no significant difference

Table 26. Least significant difference (P = 0.10) between mean wheat yields by tillage from the Glenharold and Knife River tillage locations.

Location	Year 1989	1990	1991	1992
	($Mg\ ha^{-1}$)			
Glenharold	NS	NS	NS	0.05
Knife River	0.11	NS	0.12	NS

NS indicates no significant difference.

Table 27. Least significant differences (P=0.10) among mean wheat yields grown on prior-cropping strips from the Glenharold and Knife River tillage locations.

Main Effects	Glenharold	Knife River
	($Mg\ ha^{-1}$)	
Tillage	NS	NS
Prior Crop	0.22	0.13
Tillage x Prior Crop	NS	0.19

NS indicates no significant difference.

Table 28. Mean soil fertility at planting (June 1989) and at time of prior cropping strip installation (October, 1991) from the Knife River and Glenharold locations.

Crop	Depth (cm)	N	P	K
			(kg/ha)	
		Knife River - June 1989		
Small Grain	0-15	116	25	330
	15-60	171		
Forages	0-15	120	105	364
	15-60	171		
		October 1991		
Small Grain	0-15	31	23	403
	15-60	193		
Alfalfa	0-15	26	19	336
	15-60	47		
Native Mix	0-15	11	19	370
	15-60	34		
Precrop Mix	0-15	18	17	330
	15-60	74		
Pubescent Wheatgrass	0-15	10	17	347
	15-60	67		
Tall Wheatgrass	0-15	16	18	342
	15-60	86		
		Glenharold - June, 1989		
Small Grain	0-15	181	18	431
	15-60	114		
Forages	0-15	160	54	431
	15-60	114		
		October 1991		
Small Grain	0-15	74	16	465
	15-60	137		
Alfalfa	0-15	26	8	476
	15-60	31		
Native Mix	0-15	21	9	543
	15-60	22		
Precrop Mix	0-15	23	9	510
	15-60	68		
Pubescent Wheatgrass	0-15	17	9	521
	15-60	26		
Tall Wheatgrass	0-15	22	10	482
	15-60	27		

+Small grains were fertilized annually as needed to produce 2.7 Mg/ha yields. Forages were not fertilized after June 1989, and remaining forages were harvested annually after yield samples were taken.

Table 29. Least significant differences (P = 0.10) between tillage treatment mean forage yields from the Glenharold and Knife River tillage locations.

Location	Year		
	1990	1991	1992
		($Mg\ ha^{-1}$)	
		Alfalfa	
Glenharold	NS	NS	NS
Knife River	NS	NS	NS
		Native Mix	
Glenharold	NS	NS	NS
Knife River	NS	NS	NS
		Precrop Mix	
Glenharold	NS	NS	0.27
Knife River	NS	NS	NS
		Pubescent Wheatgrass	
Glenharold	NS	NS	NS
Knife River	NS	NS	NS
		Tall Wheatgrass	
Glenharold	NS	NS	NS
Knife River	NS	NS	NS

Table 30. Least significant difference (P = 0.10) among mean root length and mass densities from the Glenharold tillage location.

Main Effects	Depth (m) 0-0.15	0.3-0.45	0.6-0.75	0.9-1.05	1.2-1.35
			Root Length Densities		
Year	0.6	0.3	0.1	<0.1	<0.1
Tillage	0.3	0.2	NS	NS	NS
Year x Tillage	0.7	NS	0.1	0.1	NS
Crop	0.7	0.4	0.1	0.1	<0.1
Year x Crop	1.6	1.0	0.2	0.2	0.1
Tillage x Crop	1.0	0.5	0.1	NS	NS
Year x Tillage x Crop	NS	1.2	0.3	0.3	NS
			Root Mass Densities		
Year	<0.01	<0.01	<0.01	<0.01	<0.01
Tillage	<0.01	<0.01	NS	NS	NS
Year x Tillage	<0.01	<0.01	<0.01	<0.01	NS
Crop	<0.01	<0.01	<0.01	<0.01	NS
Year x Crop	<0.01	<0.01	<0.01	<0.01	<0.01
Tillage x Crop	<0.01	<0.01	<0.01	<0.01	NS
Year x Tillage x Crop	<0.01	<0.01	<0.01	<0.01	NS

NS indicates no significant difference.

Table 31. Least significant difference (P = 0.10) among mean root length and mass densities from the Knife River tillage location.

Main Effects	Depth (m)				
	0-0.15	0.3-0.45	0.6-0.75	0.9-1.05	1.2-1.35
			Root Length Densities		
Year	0.8	0.2	0.1	0.1	0.1
Tillage	NS	0.1	0.1	<0.1	<0.1
Year x Tillage	0.4	0.2	0.1	0.1	0.1
Crop	0.6	0.2	0.1	0.1	0.1
Year x Crop	1.5	0.4	0.3	0.1	0.1
Tillage x Crop	0.9	0.2	0.2	0.1	0.2
Year x Tillage x Crop	2.1	0.5	0.4	0.2	0.5
			Root Mass Densities		
Year	<0.01	<0.01	<0.01	<0.01	<0.01
Tillage	<0.01	<0.01	<0.01	<0.01	<0.01
Year x Tillage	<0.01	<0.01	NS	<0.01	<0.01
Crop	<0.01	<0.01	<0.01	<0.01	<0.01
Year x Crop	<0.01	<0.01	<0.01	<0.01	<0.01
Tillage x Crop	<0.01	NS	<0.01	<0.01	<0.01
Year x Tillage x Crop	<0.01	NS	<0.01	<0.01	<0.01

NS indicates no significant difference.

Table 32. Results of regressions of mean root length and mass densities on soil physical properties from the Glenharold and Knife River tillage locations.

Parameter	Coefficient	
Glenharold		
Root Length Density (km m^{-3})		
Intercept	85.1	$R^2 = 0.33$
Cone Index (MPa)	- 3.1	
Wet Bulk Density (Mg m^{-3})	-34.5	
Root Mass Density (kg m^{-3})		
Intercept	23.8	$R^2 = 0.11$
Cone Index (MPa)	- 1.0	
Wet Bulk Density (Mg m^{-3})	- 9.8	
Knife River		
Root Length Density (km m^{-3})		
Intercept	86.3	$R^2 = 0.23$
Cone Index (MPa)	- 1.0	
Wet Bulk Density (Mg m^{-3})	-35.9	
Root Mass Density (kg m^{-3})		
Intercept	28.1	$R^2 = 0.07$
Cone Index (MPa)	- 0.3	
Wet Bulk Density (Mg m^{-3})	-12.0	

Table 33. Least significant difference ($P = 0.10$) among mean soil bulk densities obtained in 1979 and 1990 from the Falkirk trench location.

	Depth (m)			
Main Effect	**0-0.3**	**0.3-0.6**	**0.6-0.9**	**0.9-1.2**
			(Mg m^{-3})	
Year	NS	NS	NS	NS
Topsoil Depth	NS	0.03	NS	NS
Year x Topsoil Depth	NS	0.04	NS	NS
Subsoil	0.08	0.10	0.13	NS
Year x Subsoil	0.11	NS	NS	0.25
Topsoil Depth x Subsoil	0.15	NS	NS	NS
Year x Topsoil Depth x Subsoil	NS	NS	NS	NS

NS indicates no significant difference.

Table 34. Least significant difference (P = 0.10) among mean soil bulk densities from the Center and Falkirk topography locations.

Main Effect	Depth (m)				
	0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5
			($Mg\ m^{-3}$)		
			Center		
			Forage Area		
Year	NS	0.08	NS	NS	0.02
Position	NS	NS	NS	NS	NS
Year x Position	0.10	NS	NS	NS	NS
			Small Grain Area		
Year	0.04	NS	NS	0.14	NS
Position	NS	0.12	NS	NS	NS
Year x Position	NS	NS	NS	NS	NS
			Falkirk		
			Forage Area		
Year	NS	0.02	NS	0.12	NS
Position	NS	NS	0.15	NS	NS
Year x Position	NS	NS	NS	NS	NS
			Small Grain Area		
Year	NS	NS	0.11	0.16	NS
Position	NS	0.14	0.14	0.07	NS
Year x Position	NS	NS	NS	NS	NS

NS indicates no significant difference.

Figures 1-22

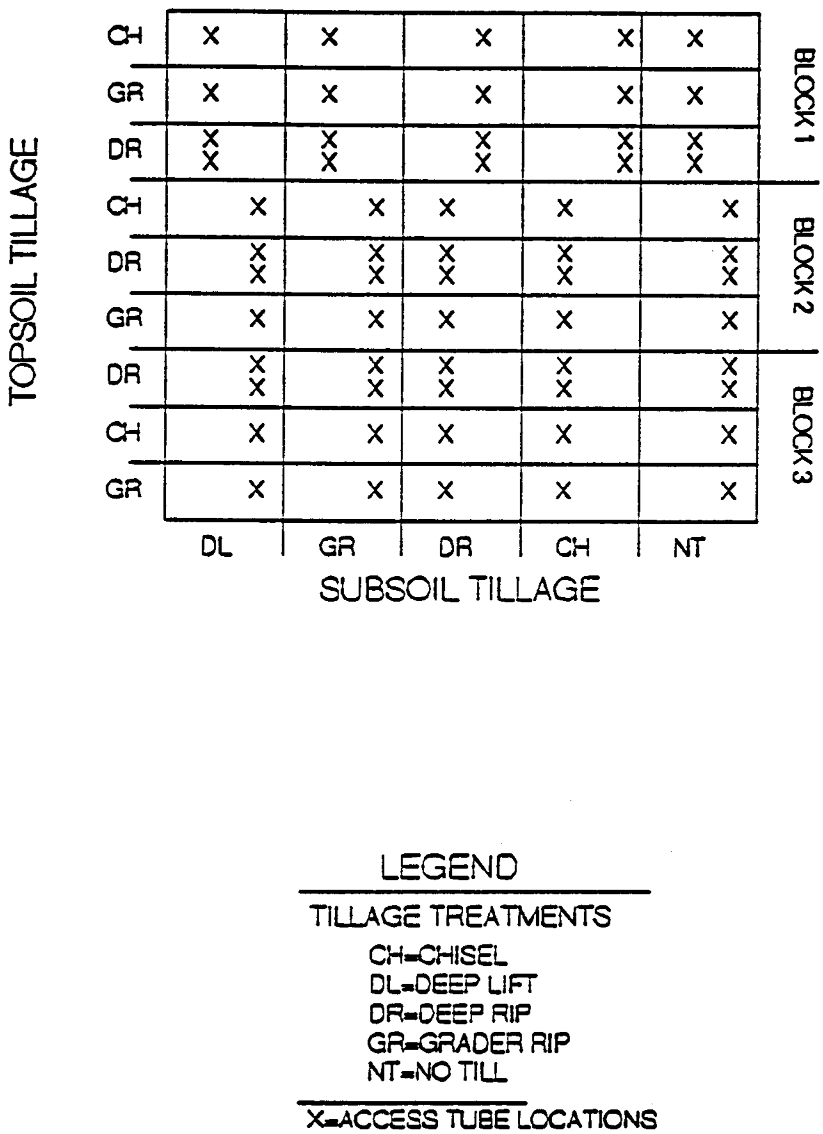


Figure 1. Plot design for the topsoil/subsoil tillage treatment locations at Center and Coteau.

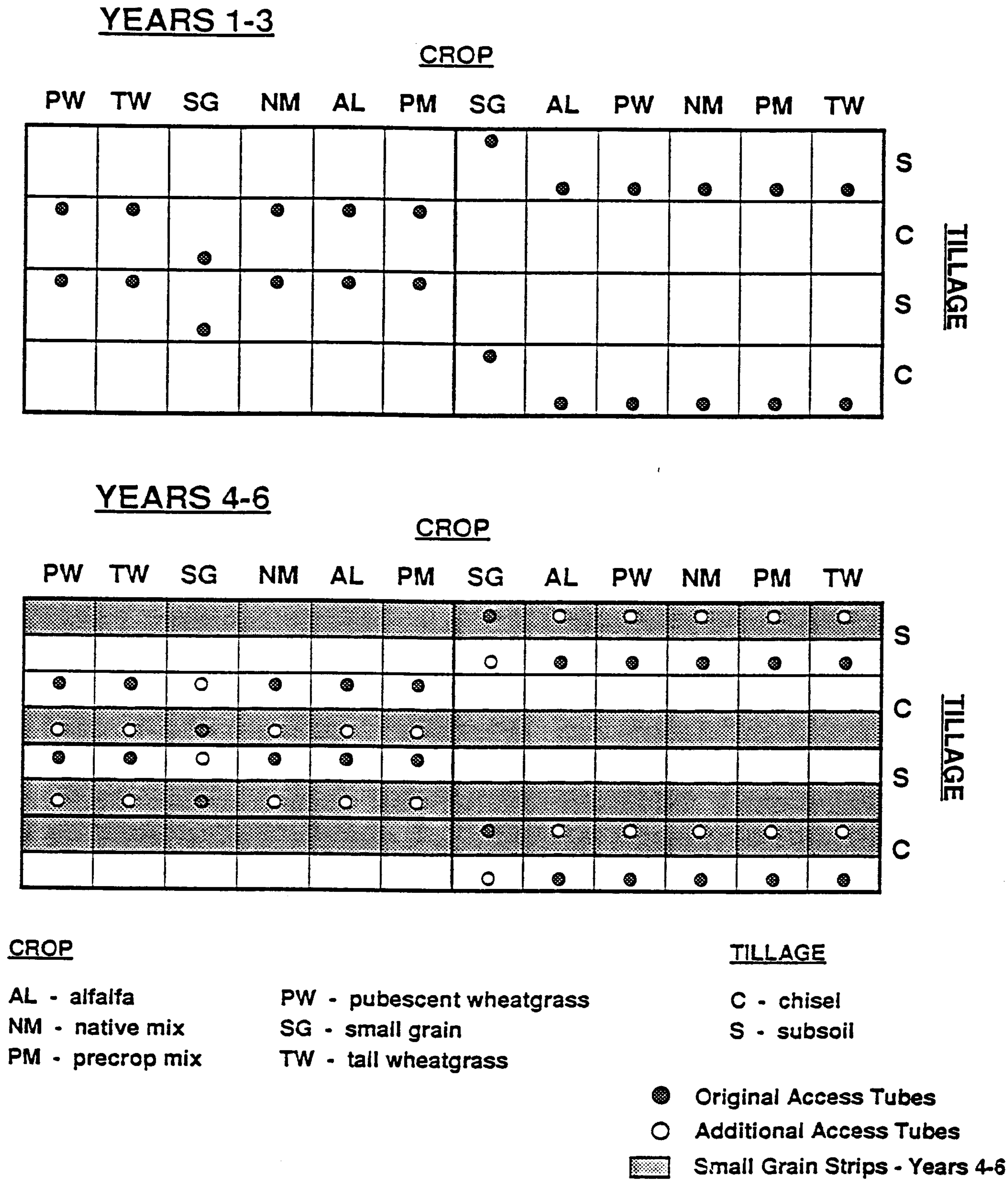


Figure 2. Plot designs for the topsoil tillage/forage treatment locations at Glenharold and Knife River.

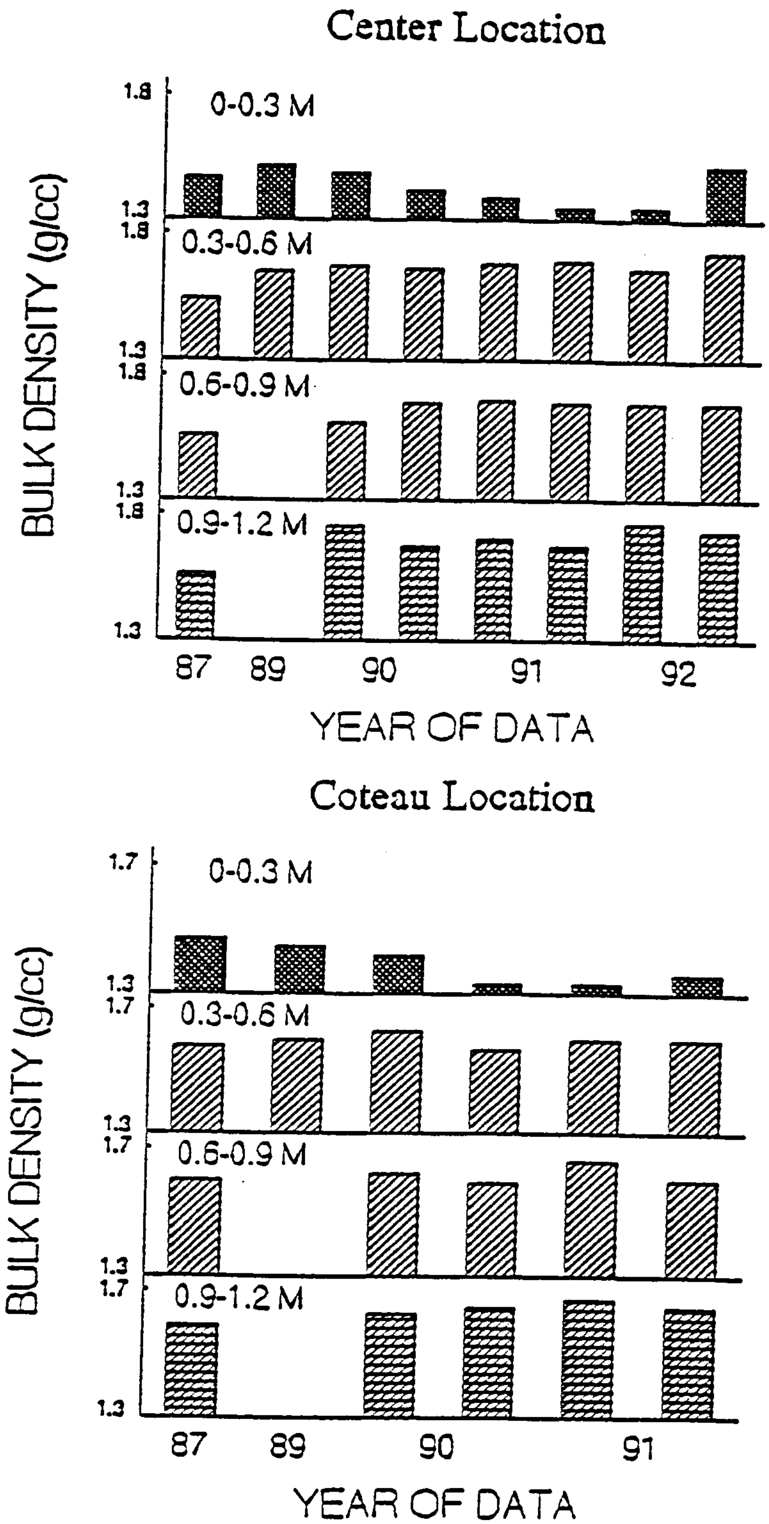


Figure 3. Mean site bulk densities by depth and sampling date at the Center and Coteau tillage locations.

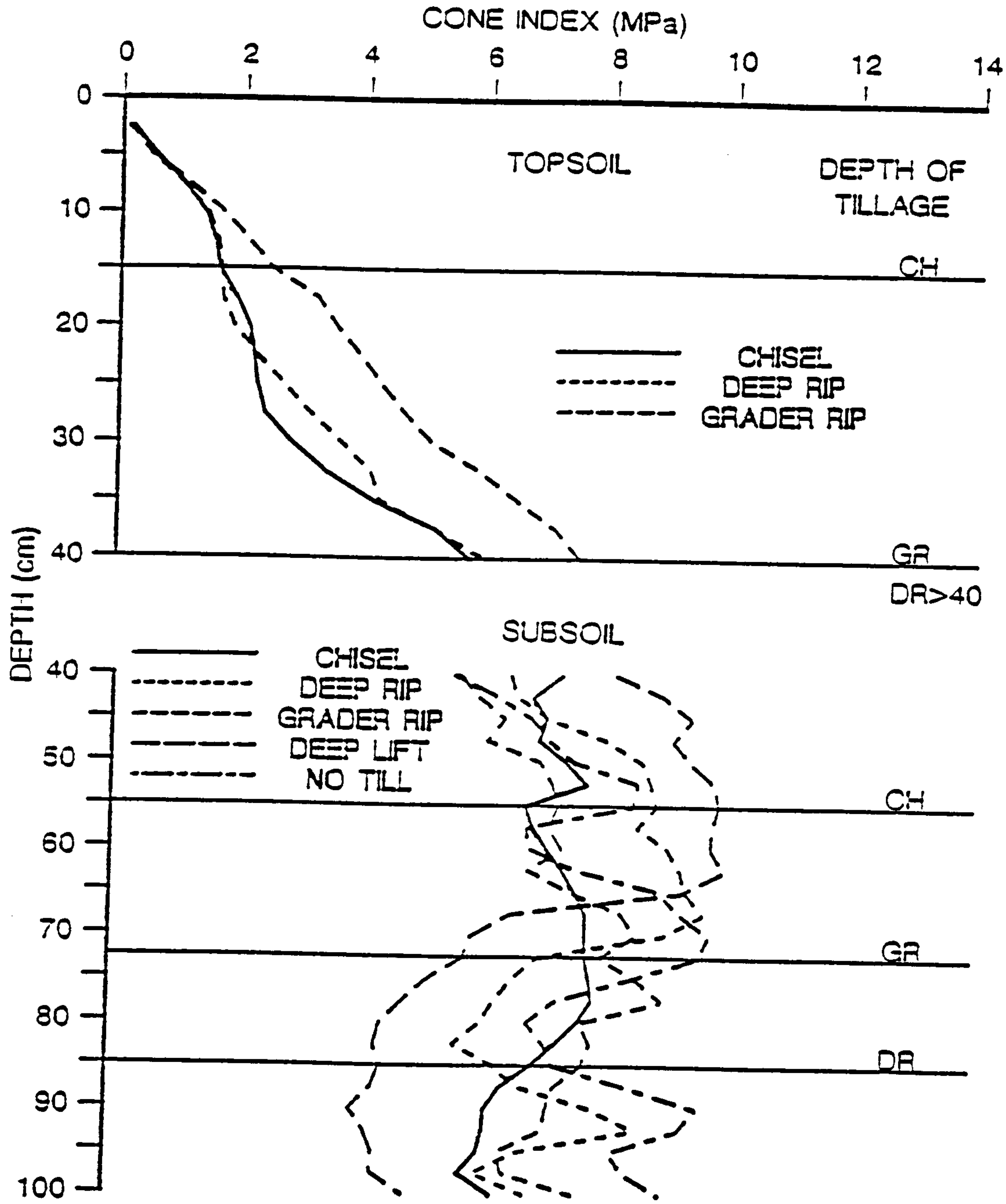
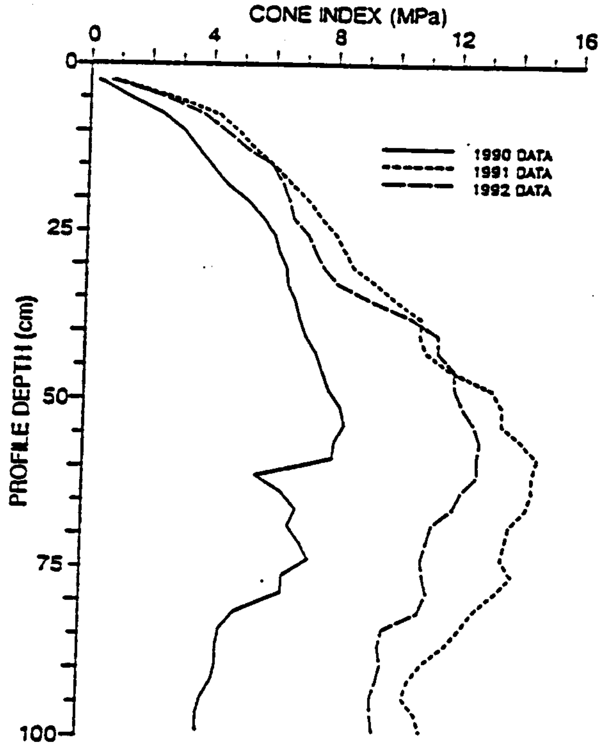


Figure 4. Mean cone index values for 1990 at the Coteau location.



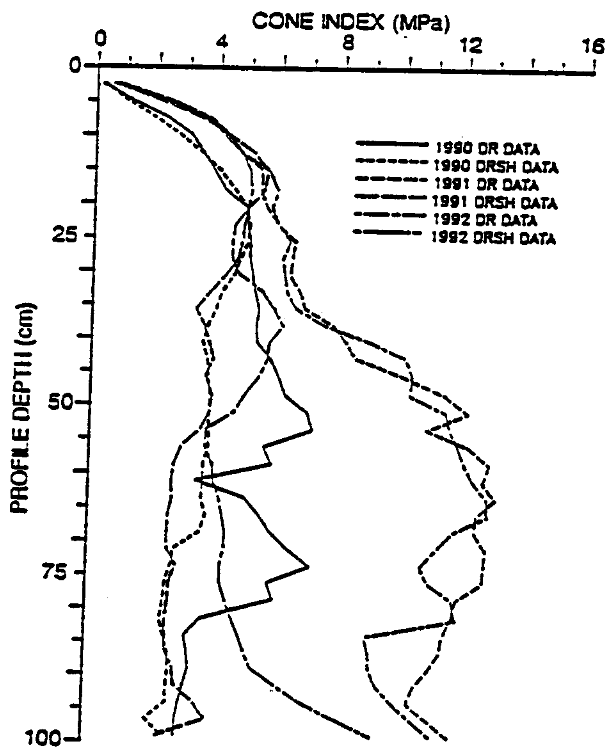


Figure 5. Changes with time for mean cone index values (no topsoil DR data in whole plot means) at the Center location and changes with time within the DR topsoil tillage subplots for between (DR) and within shank tracks (DRSH).

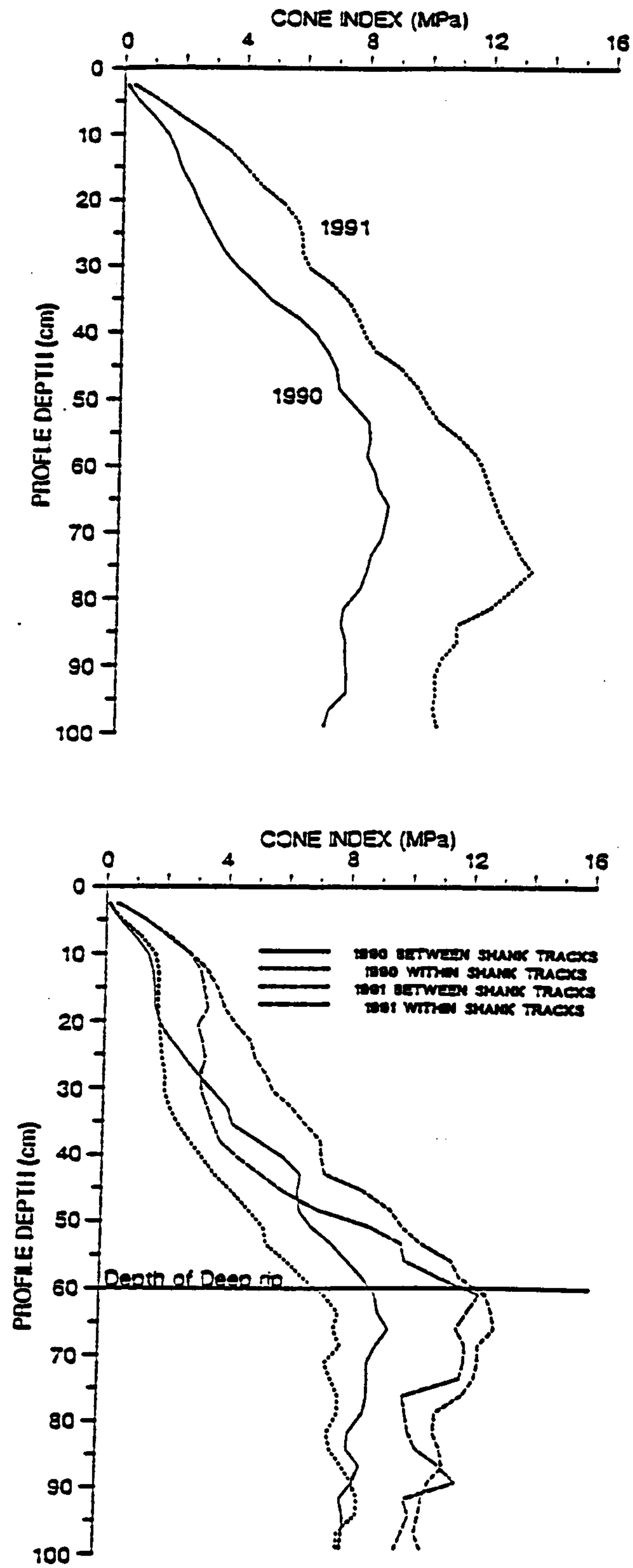


Figure 6. Changes with time for mean cone index values (no topsoil DR data in whole plot means) at the Coteau location and changes with time within the DR topsoil tillage subplots.

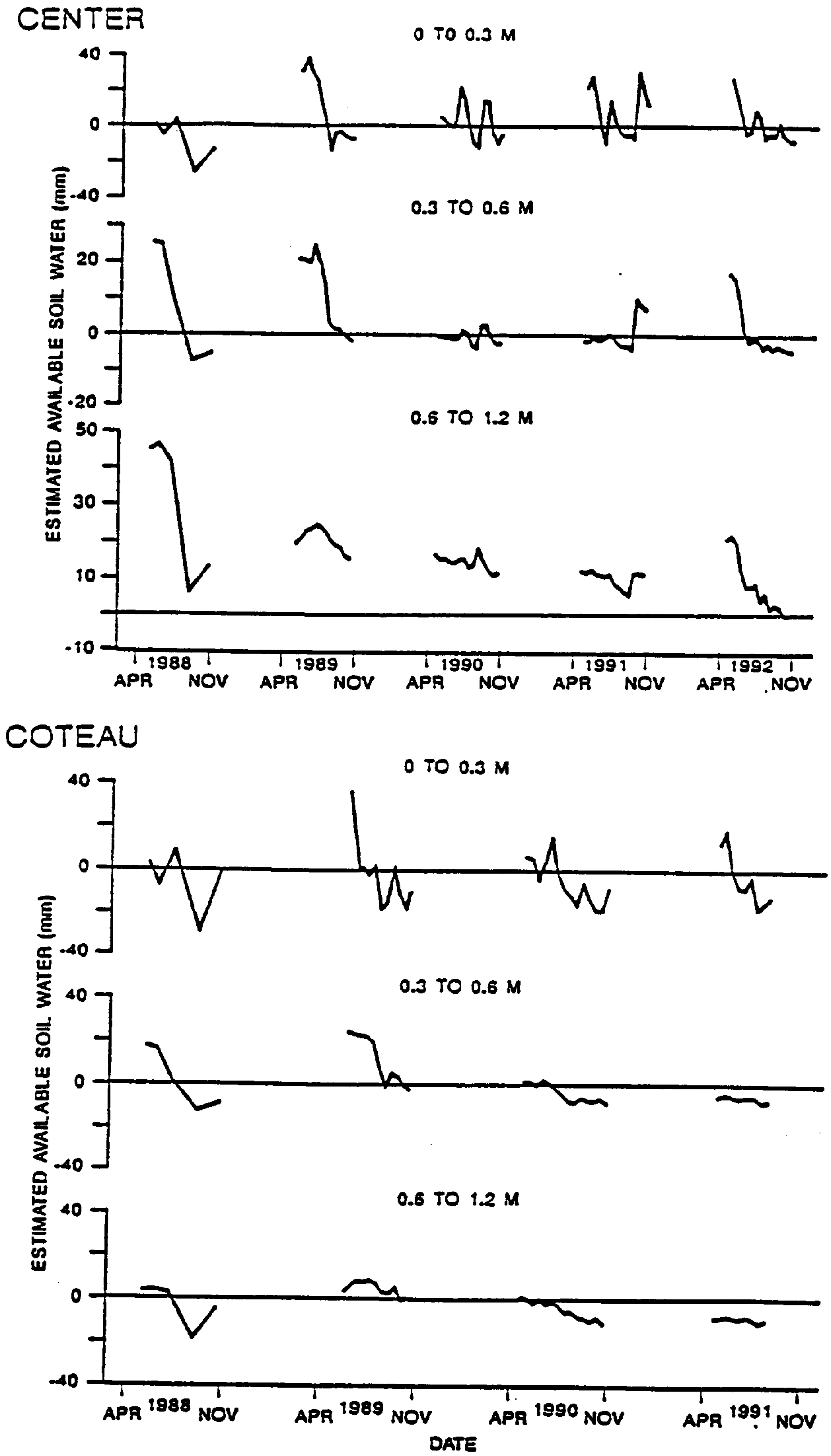


Figure 7. Mean available soil water with time at the topsoil/subsoil tillage locations.

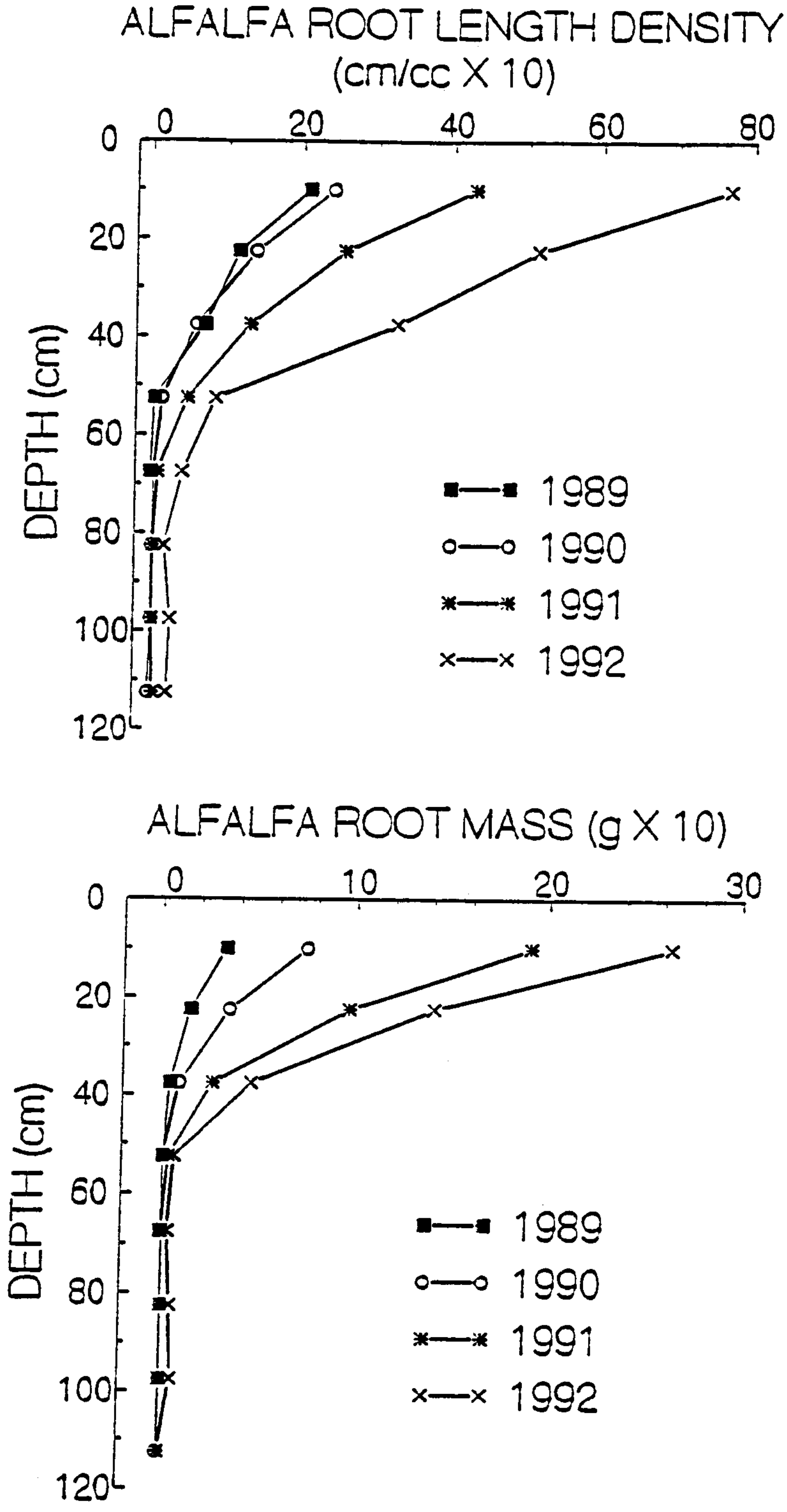


Figure 8. Mean changes by sample mid-depths for root length density and root mass for alfalfa at the Center location.

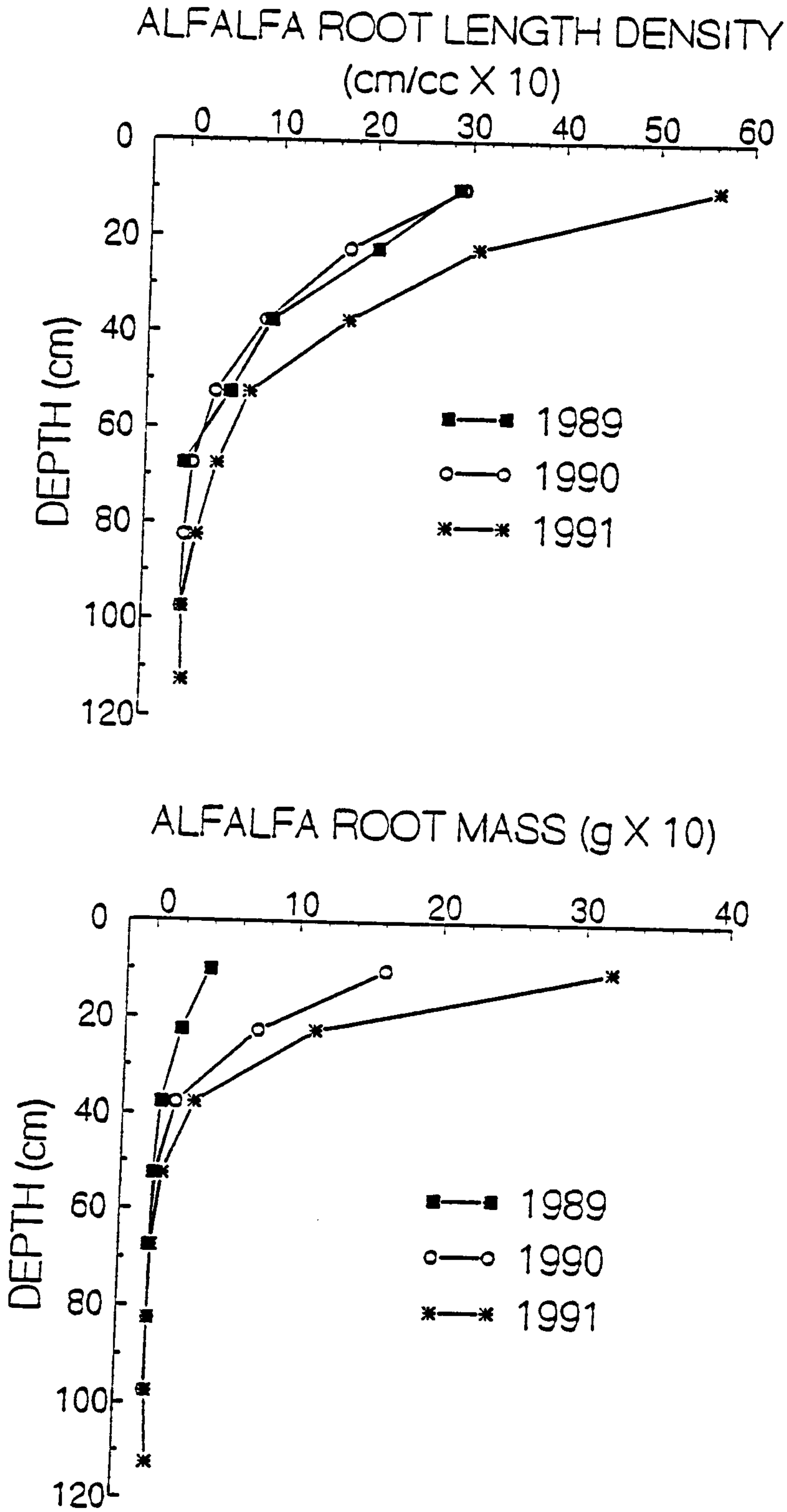


Figure 9. Mean changes by sample mid-depths for root length density and root mass for alfalfa at the Coteau location.

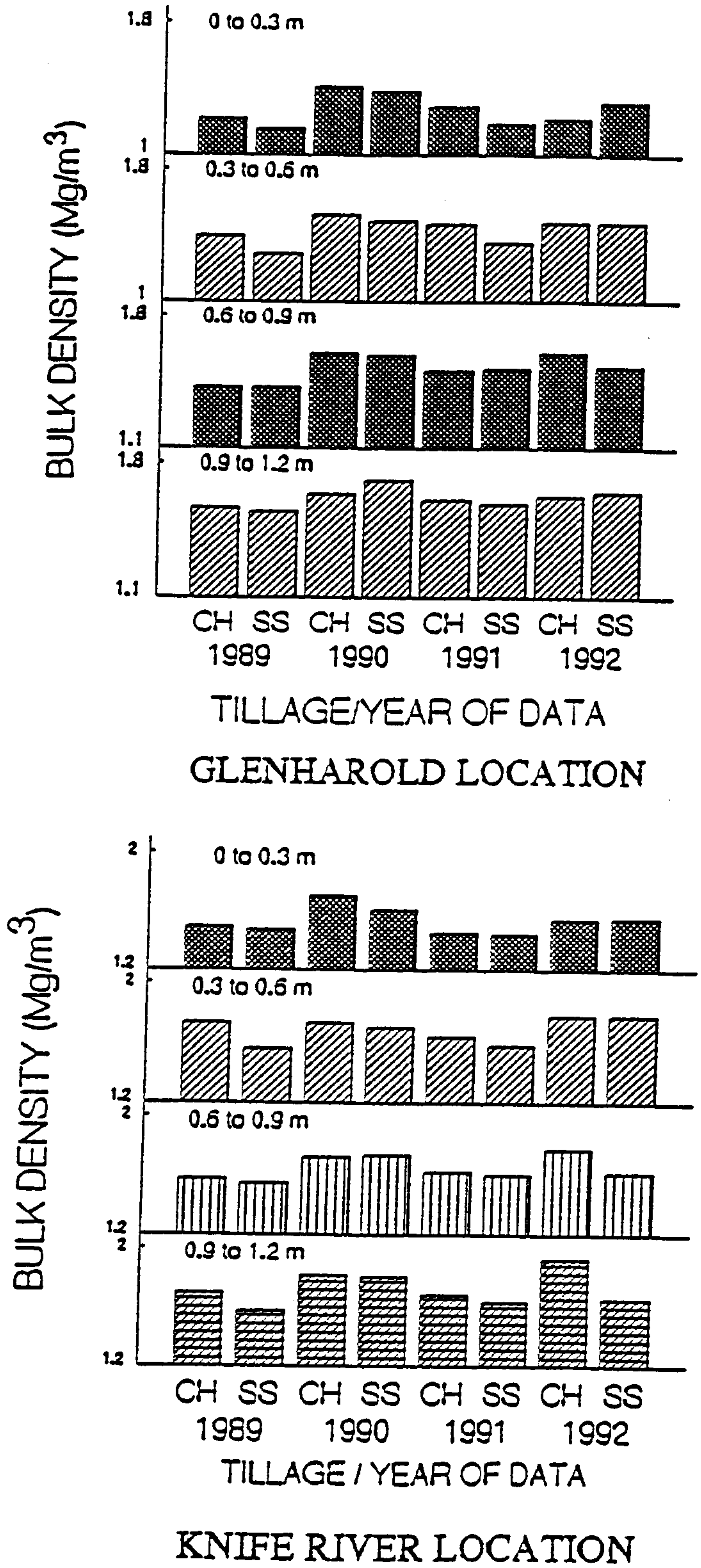
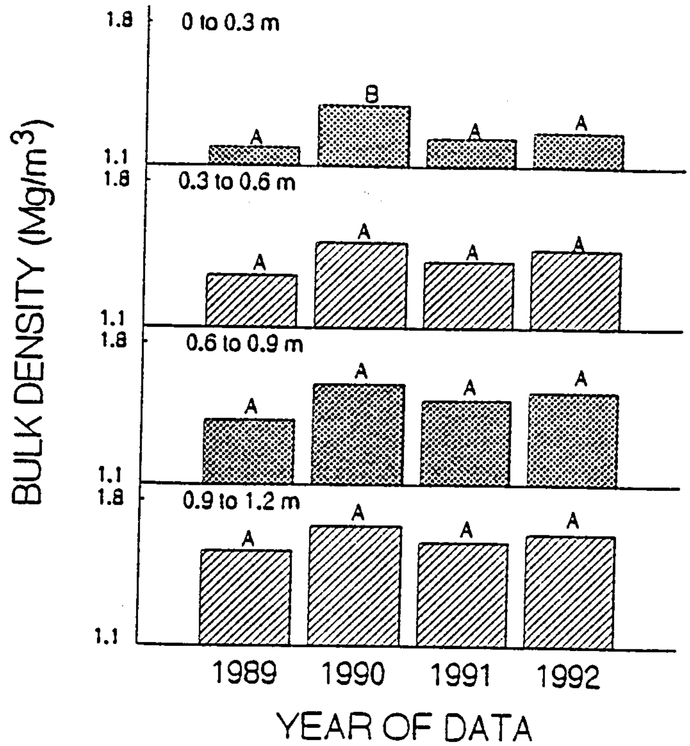
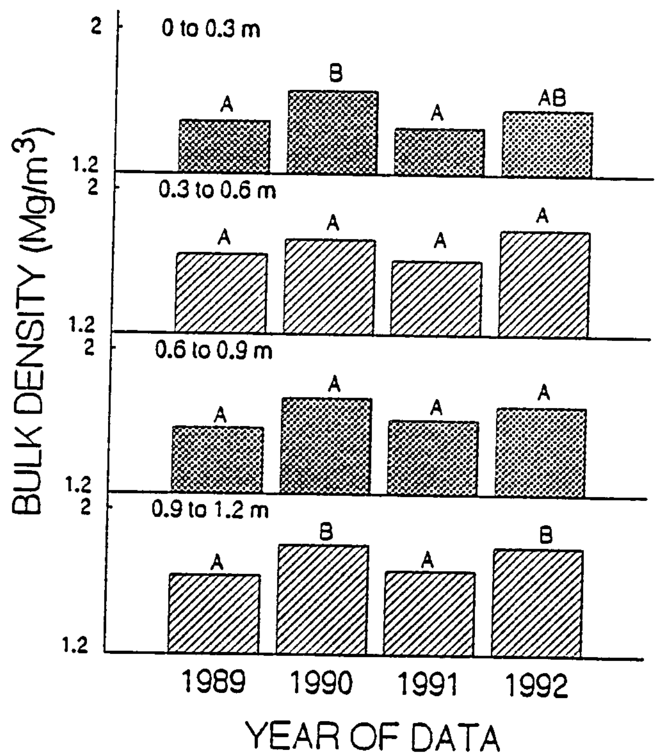


Figure 10. Mean tillage bulk densities averaged over crops at the two locations.



GLENHAROLD LOCATION



KNIFE RIVER LOCATION

Figure 11. Mean location bulk densities by depth with time (values within depths with the same letter are not significantly different at the P = 0.10 level).

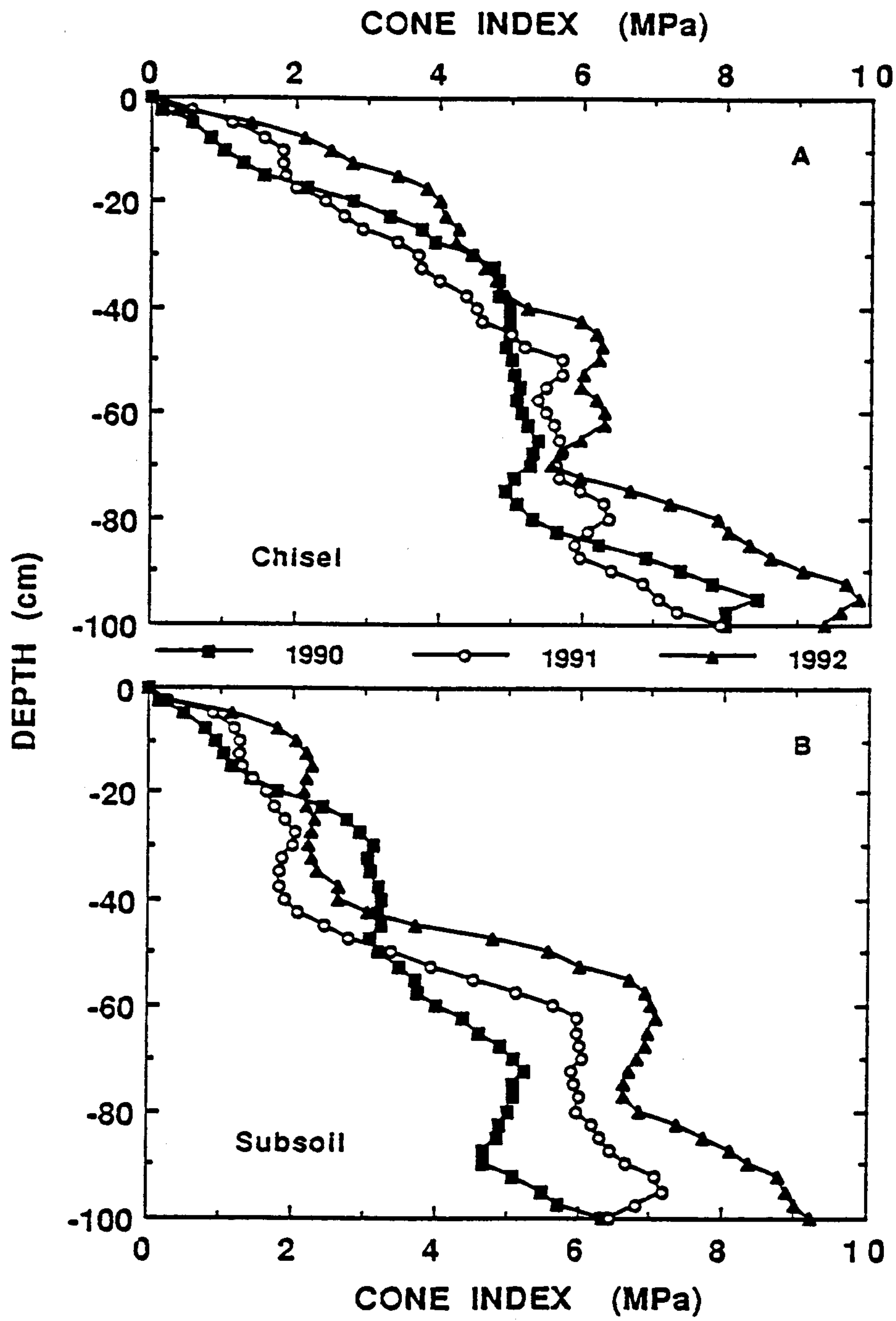


Figure 12. Mean penetrometer cone indices from the (a) chisel and (b) subsoil tillage treatments at the Glenharold tillage location.

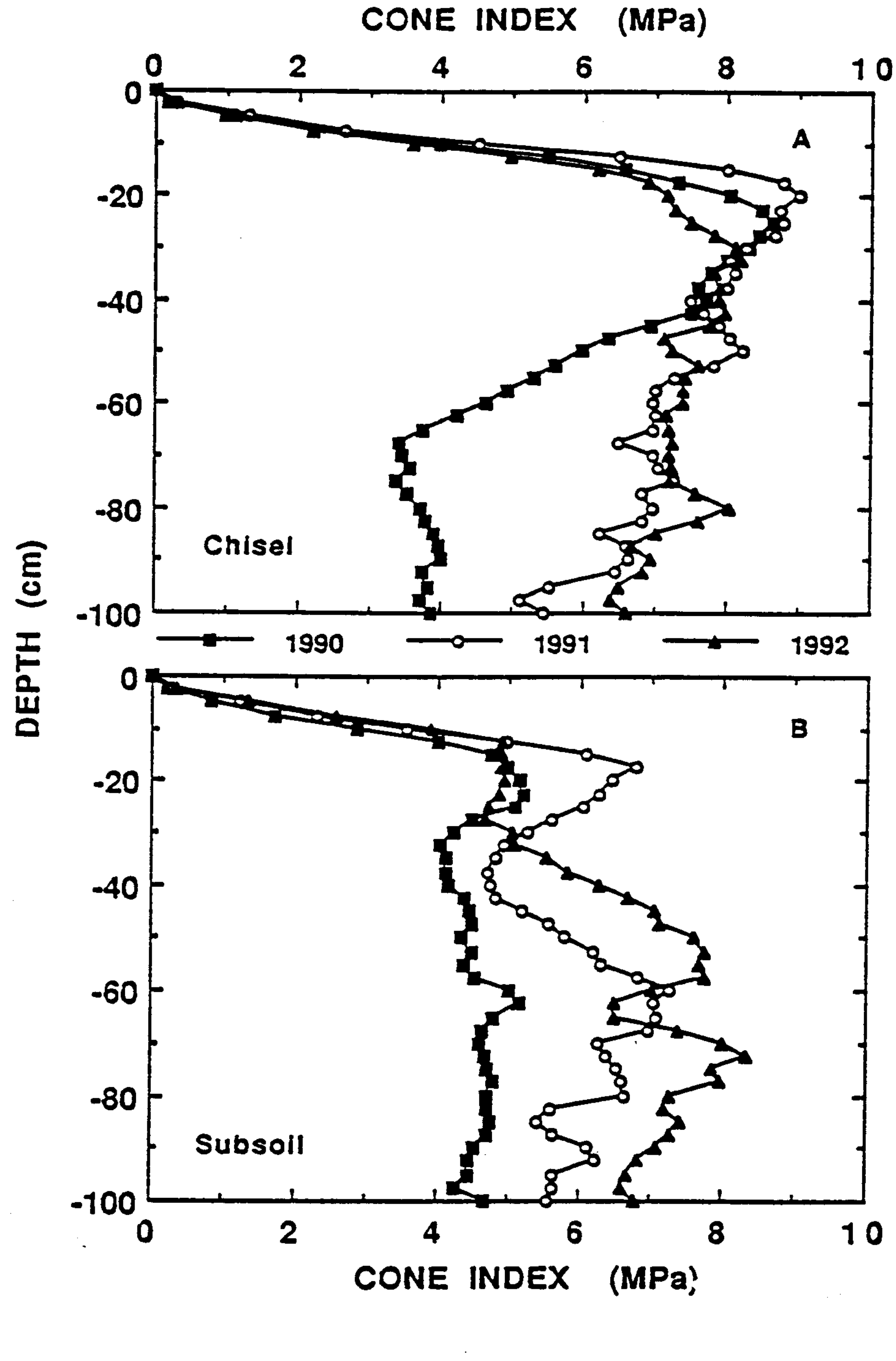


Figure 13. Mean penetrometer cone indices from the (a) chisel and (b) subsoil tillage treatments at the Knife River tillage location.

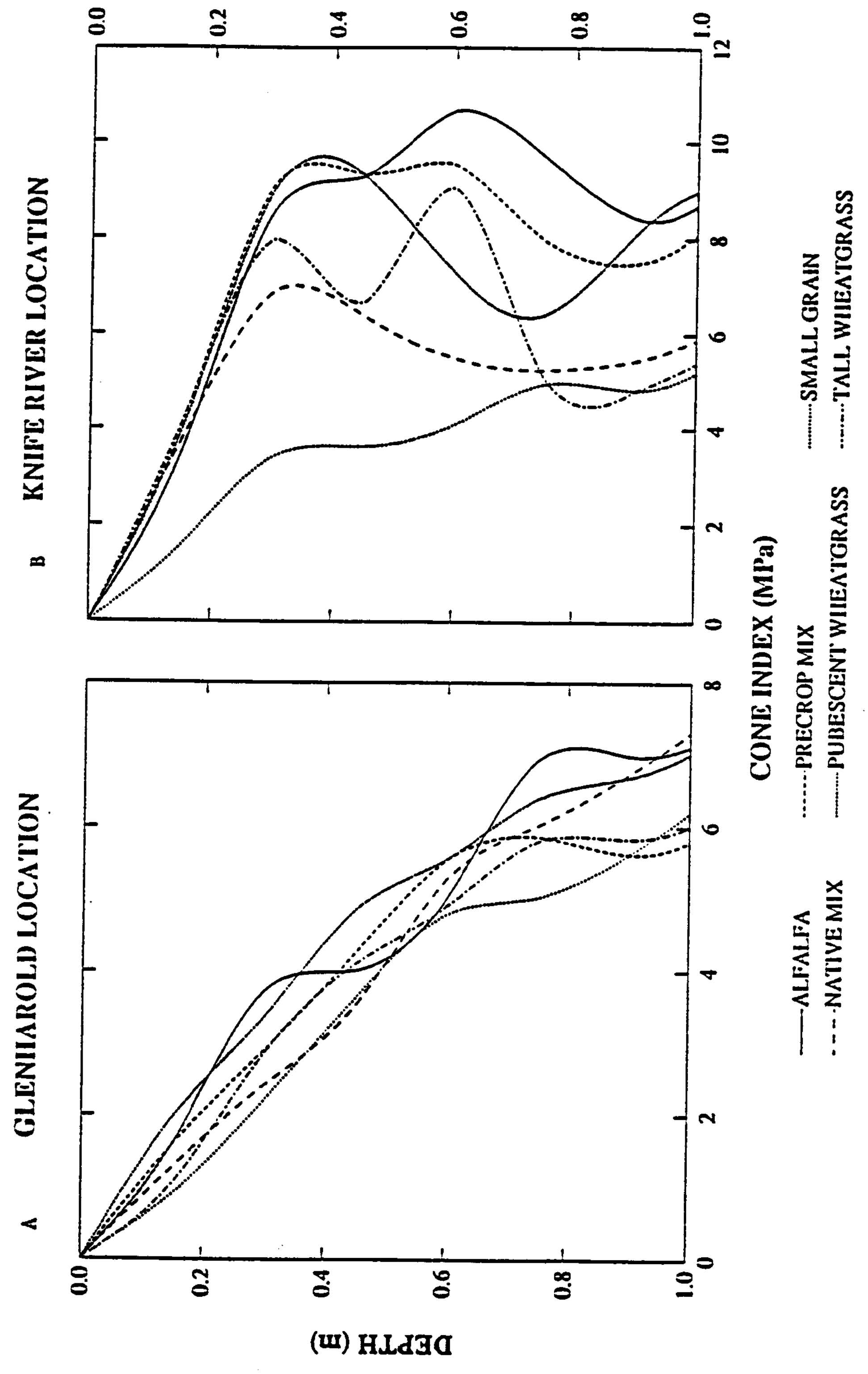


Figure 14. Mean penetrometer cone indices by crop from the (a) Glenharold and (b) Knife River tillage locations.

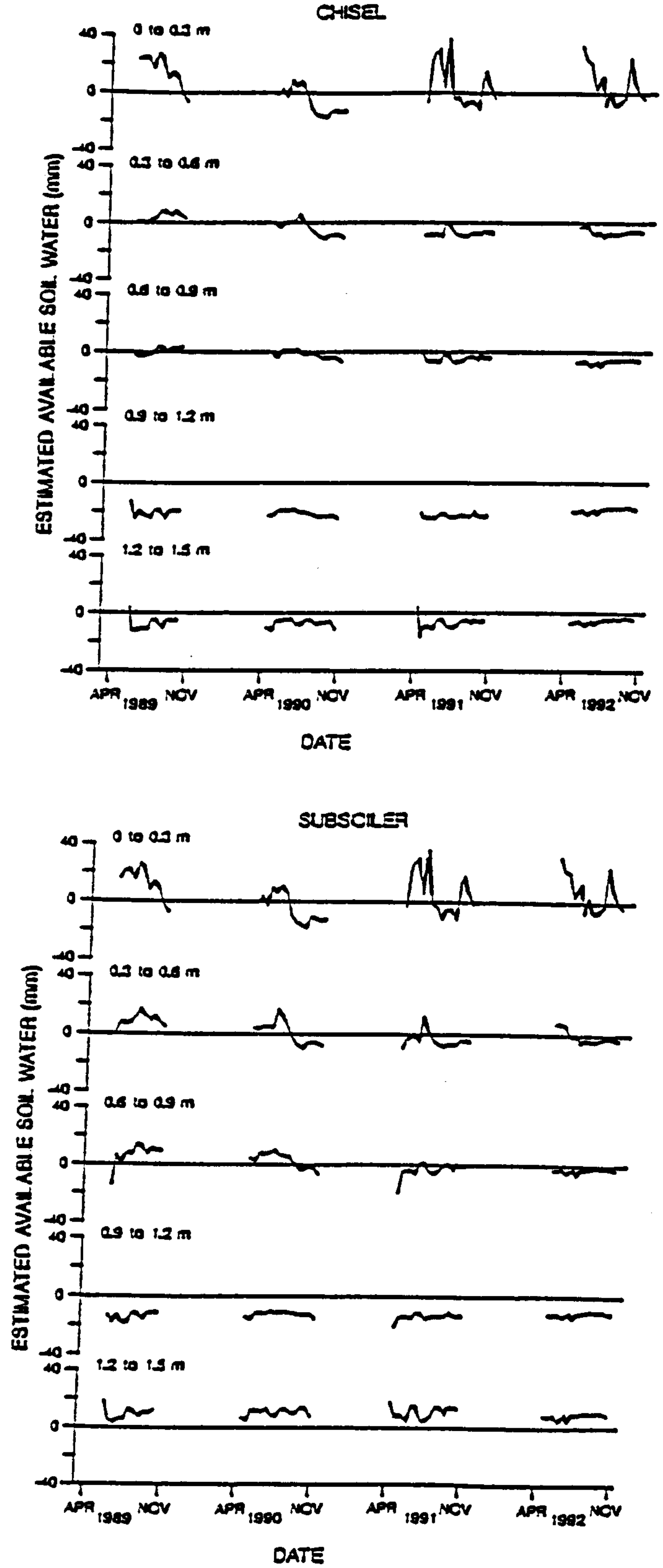
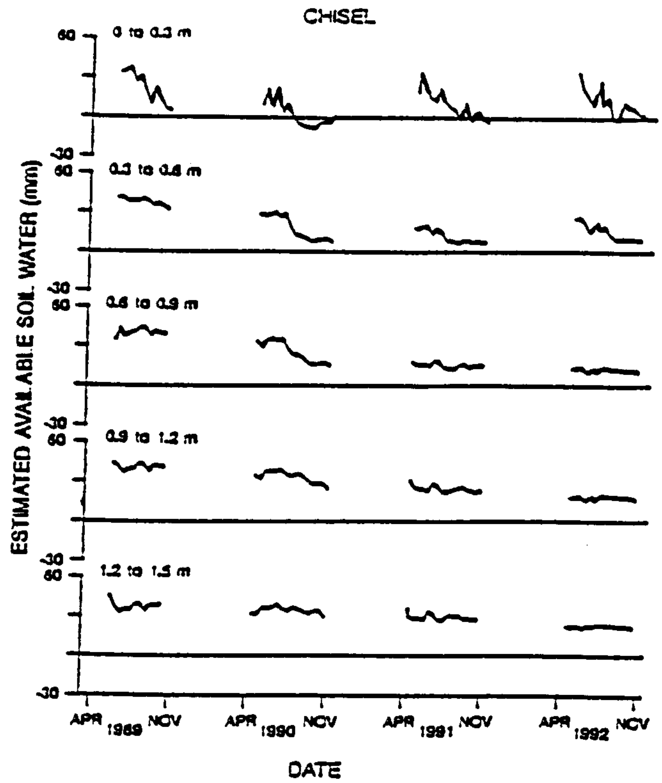


Figure 15. Mean available water from the beginning to the end of the growing seasons for the chisel and subsoil tillage treatments at the Glenharold tillage location.



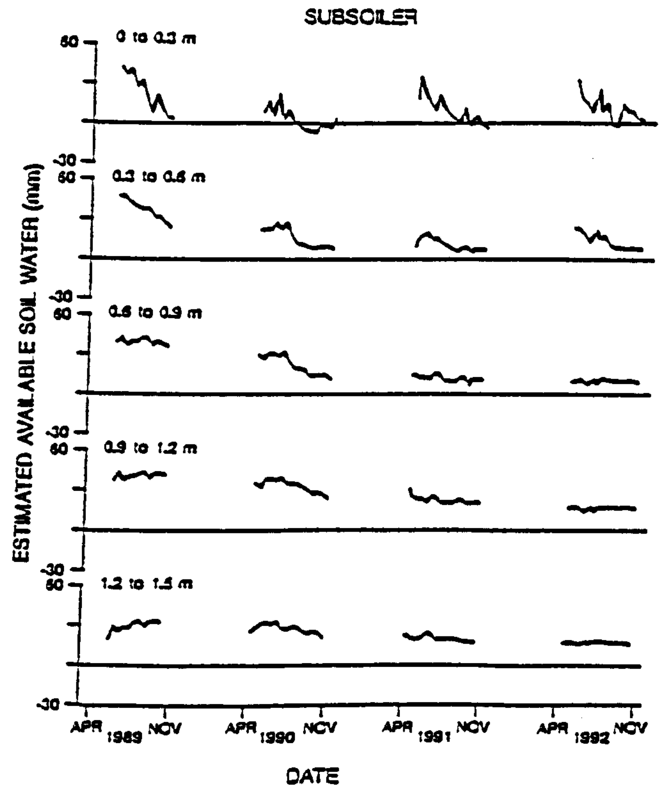
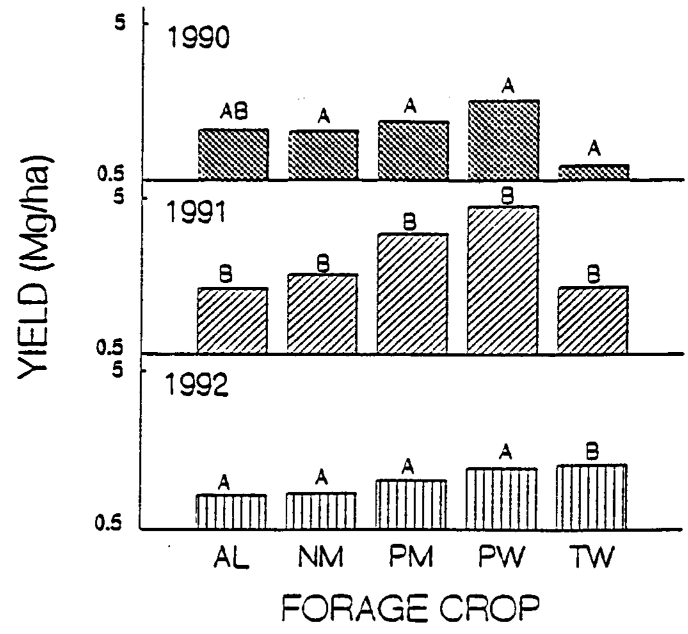
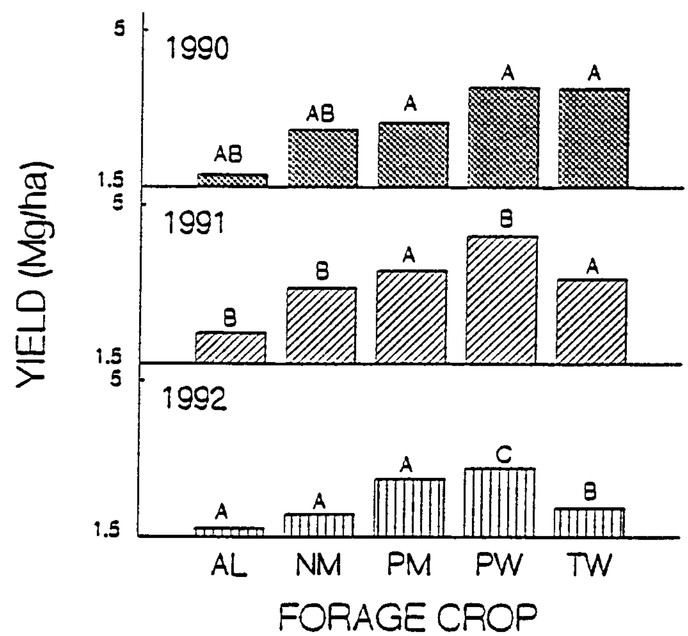


Fig. 16. Mean available water from the beginning to the end of the growing seasons for the chisel and subsoil tillage treatments at the Knife River tillage location.



GLENHAROLD FORAGE YIELDS



KNIFE RIVER FORAGE YIELDS

Fig. 17. Mean yearly forage yields by crop at the tillage locations (values by crops with the same letter are not significantly different at the P = 0.10 level).

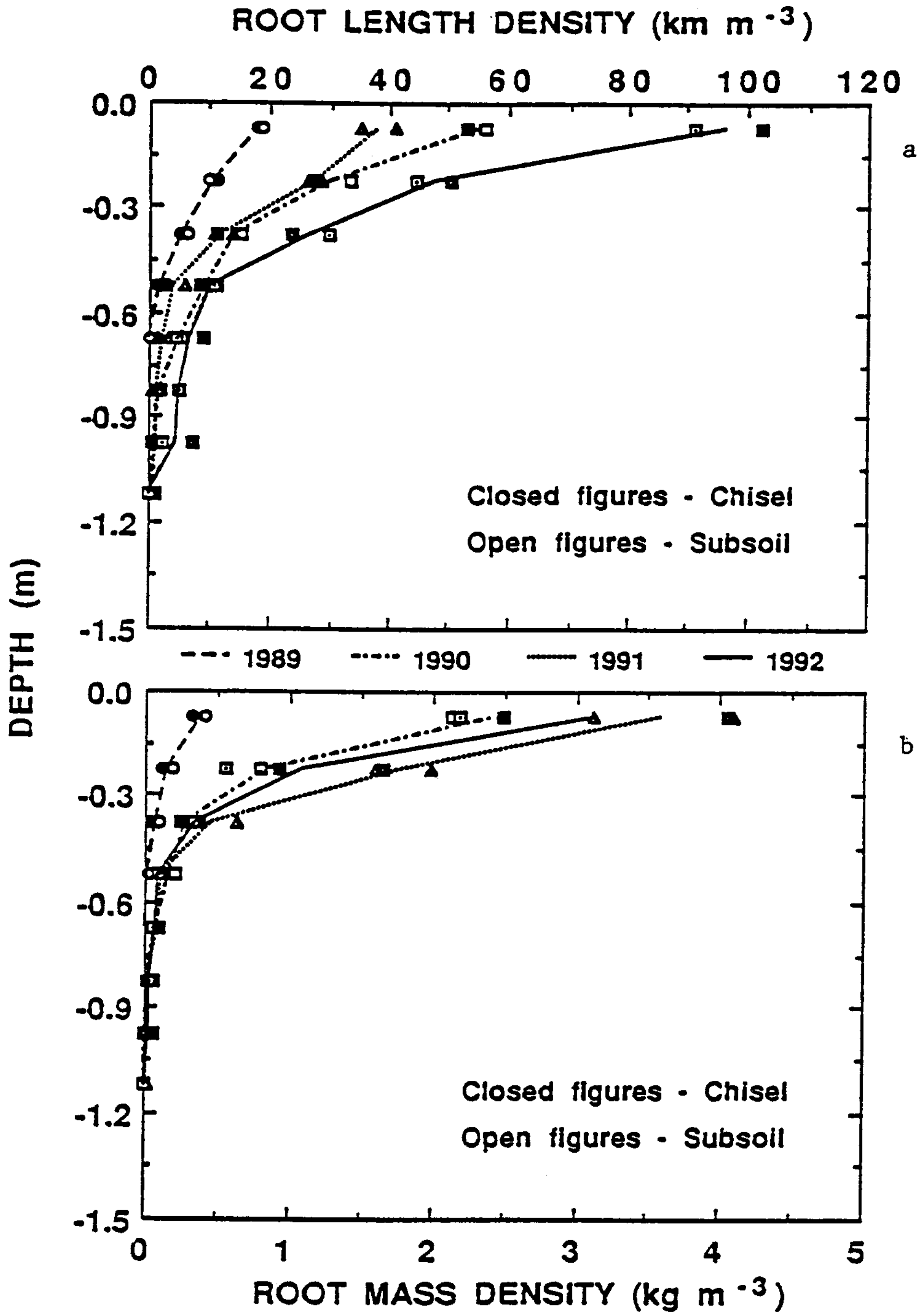


Figure 18. Mean root (a) length and (b) mass densities from the Glenharold tillage location.

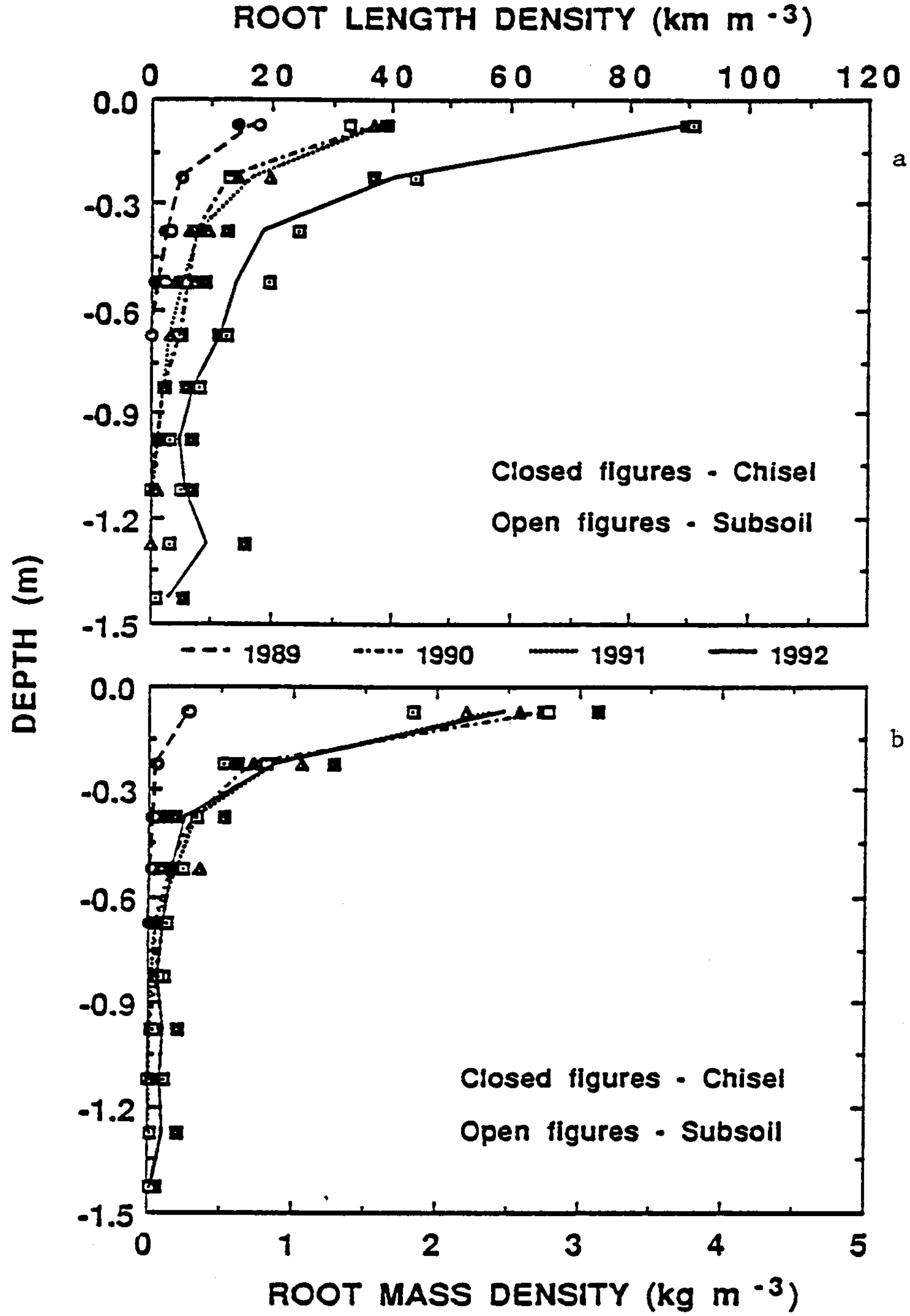


Figure 19. Mean root (a) length and (b) mass densities from the Knife River tillage location.

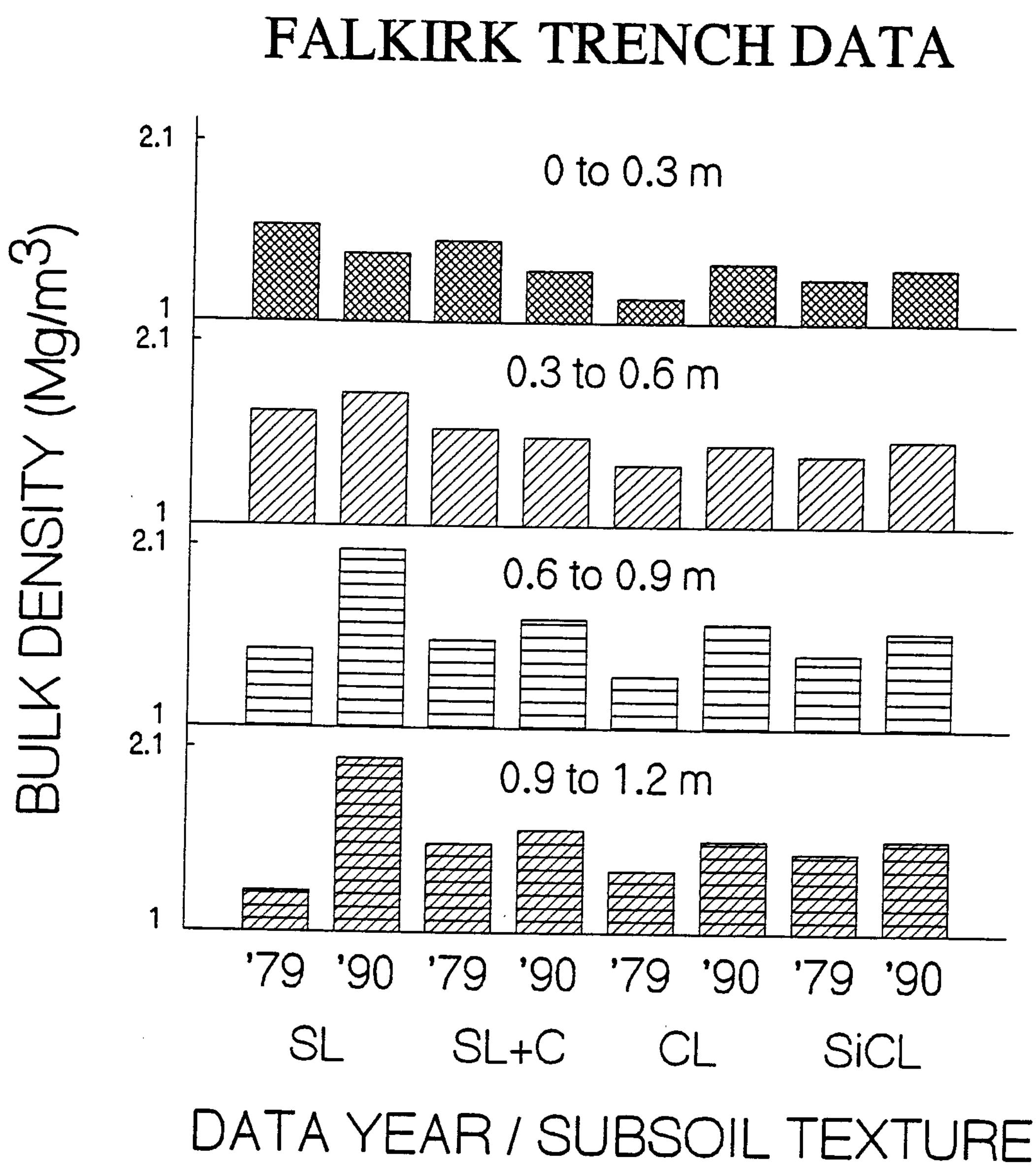


Figure 20. Mean bulk densities by subsoil textures (averaged over topsoil depth) with time at the Falkirk trench site.

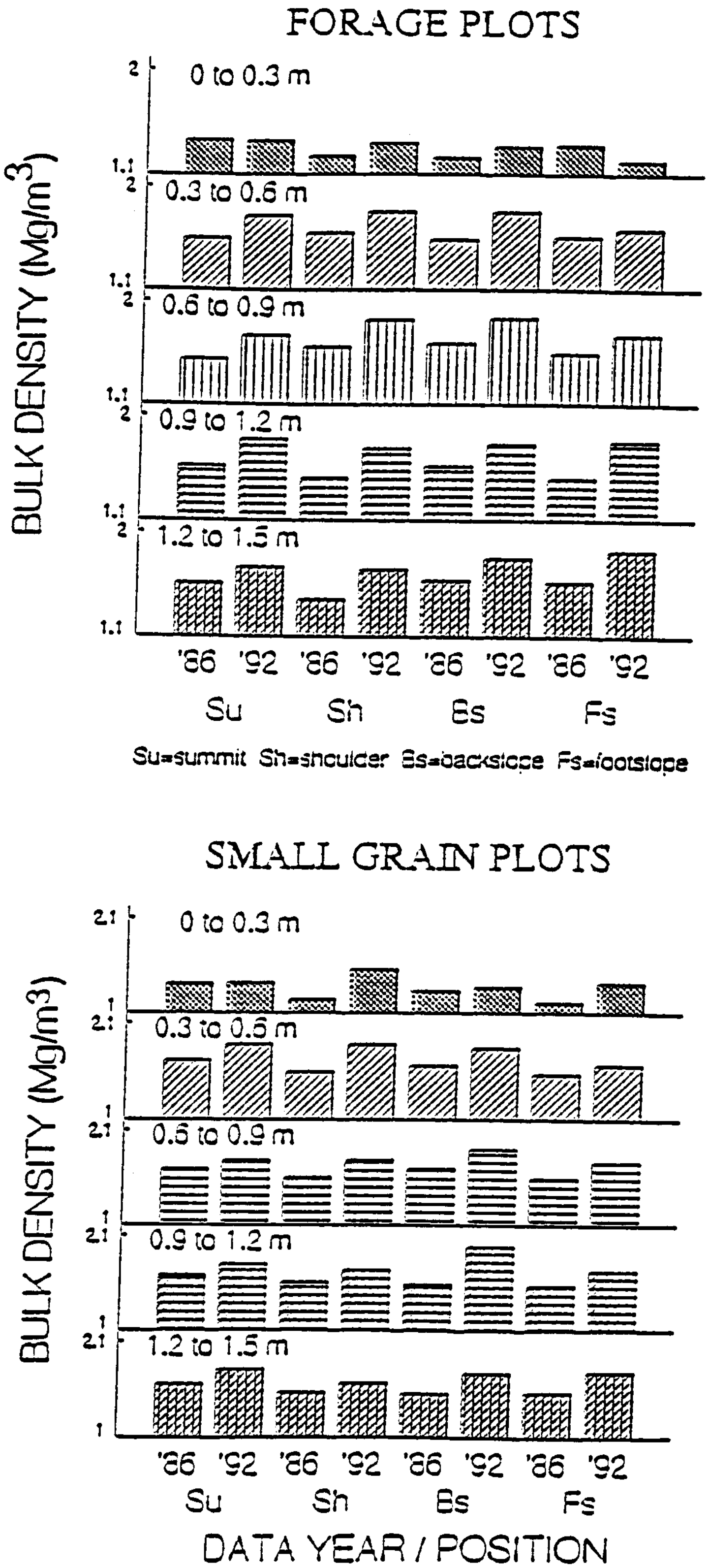


Figure 21. Mean bulk density changes with time by topography position and crop at the Center location.

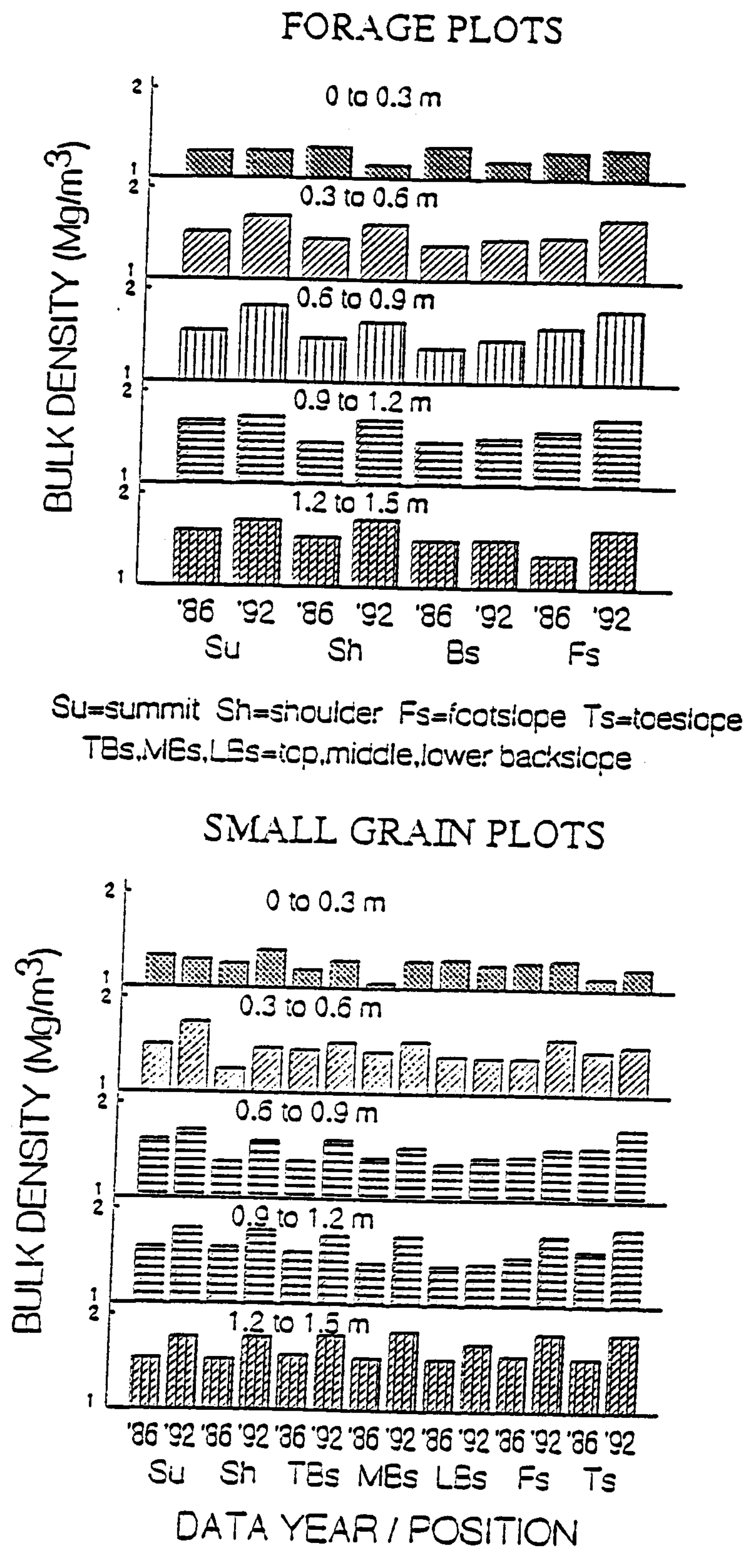


Figure 22. Mean bulk density changes with time by topography position and crop at the Falkirk location.

APPENDIX TABLES 1-36

Table A1. Mean chemical and physical characteristics of the Center tillage study from the 1987 access tube cores.†

	Chemical					Physical				
Depth	pH	EC	Sat.%	SAR	Org. C	VFS‡	Sand	Silt	Clay	Texture
(cm)					-%-		-%-			
0-15	7.8	0.7	45.1	0.3	2.0	17.3	44.5	39.2	16.3	Loam
15-30	7.8	0.7	44.5	0.3	1.8	16.1	44.9	38.5	16.6	Loam
30-45	7.8	0.9	42.1	0.7	1.2	13.1	55.8	28.3	15.9	Sandy Loam
45-60	7.8	0.9	40.6	0.8	0.8	10.5	62.4	23.1	14.5	Sandy Loam
60-75	7.8	0.8	41.2	0.8	---	10.8	61.8	23.5	14.7	Sandy Loam
75-90	7.8	1.1	41.0	0.8	---	10.7	61.7	23.7	14.6	Sandy Loam
90-105	7.7	1.0	41.2	1.0	---	11.0	59.8	24.8	15.4	Sandy Loam
105-120	7.7	1.1	42.1	2.0	---	14.1	57.6	26.9	15.5	Sandy Loam
120-135	7.8	1.2	43.7	3.2	---	20.8	55.5	30.1	14.4	Sandy Loam
135-150	7.9	0.8	43.0	2.2	---	23.0	58.0	27.6	14.4	Sandy Loam

†Mean of 10 replications (materials from six cores were combined to make one replication).

‡Based on total sample weight.

Table A2. Mean chemical and physical characteristics of the Coteau tillage study from the 1987 access tube cores.[†]

	Chemical					Physical				
Depth	pH	EC	Sat.%	SAR	Org. C	VFS[‡]	Sand	Silt	Clay	Texture
(cm)					-%-	-%-				
0-15	7.4	0.8	47.6	0.4	1.6	10.0	30.1	47.7	22.2	Loam
15-30	7.4	0.8	51.6	0.4	1.5	8.2	30.1	46.8	23.1	Loam
30-45	7.6	1.2	49.1	1.0	1.1	9.3	36.9	40.6	22.5	Loam
45-60	7.8	1.4	46.4	1.5	0.6	10.0	47.4	31.6	21.0	Loam
60-75	7.9	1.5	47.4	1.6	---	10.6	47.4	31.2	21.4	Loam
75-90	7.9	1.3	47.8	1.5	---	10.2	48.4	30.7	20.9	Loam
90-105	7.9	2.0	50.7	2.7	---	9.9	43.8	33.1	23.1	Loam
105-120	7.8	3.7	59.9	6.0	---	9.9	35.9	37.0	27.1	Loam
120-135	7.8	5.5	76.9	12.9	---	9.6	24.7	42.3	33.0	Clay Loam
135-150	7.8	5.6	83.6	14.9	---	9.8	20.6	44.6	34.8	Clay Loam

[†]Mean of 10 replications (materials from six cores were combined to make one replication).

[‡]Based on total sample weight.

Table A3. Mean soil physical and chemical properties obtained in 1989 during tube installation at the Glenharold location.+

		Depth (m)				
		0-0.3	**0.3-0.6**	**0.6-0.9**	**0.9-1.2**	**1.2-1.5**
Sand (%)	Mean	27	20	27	42	40
	Min/Max	24/31	11/29	18/43	10/61	18/60
Silt (%)	Mean	48	47	44	34	36
	Min/Max	45/51	41/33	31/48	22/51	24/51
Clay (%)	Mean	25	33	29	24	24
	Mix/Max	21/28	28/41	24/34	14/39	15/31
Texture‡		L	CL	CL	L	L
pH	Mean	7.8	8.0	8.0	8.0	8.0
	MinMax	7.7/7.9	7.7/8.3	7.8/8.2	7.7/8.3	7.7/8.4
EC$^{\delta}$(mmhos/cm)	Mean	1.4	2.8	3.0	4.0	3.9
	Min/Max	1.0/2.0	1.6/4.0	1.8/4.2	1.6/6.3	1.5/6.3
Saturation (%)	Mean	66	80	93	95	97
	Min/Max	60/87	64/100	65/114	81/108	81/114
SAR¶	Mean	2.5	9.8	13.0	22.2	23.3
	Min/Max	1.3/4.6	3.7/15.1	5.7/22.3	12.3/30.2	15.6/28.3

+12 replications per mean.

‡L = loam and CL = clay loam.

$^{\delta}$Electrical conductivity.

¶Sodium adsorption ratio.

Table A4. Mean soil physical and chemical properties obtained in 1989 during tube installation at the Knife River location.+

		Depth (m)				
		0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5
Sand (%)	Mean	65	61	52	52	38
	Min/Max	59/70	51/68	42/62	43/61	22/53
Silt (%)	Mean	20	22	27	27	34
	Min/Max	15/26	18/25	21/32	21/34	28/44
Clay (%)	Mean	15	17	21	21	28
	Mix/Max	10/20	12/24	15/28	17/29	19/39
Texture‡		SL	SL	SCL	SCL	CL
pH	Mean	7.7	7.7	7.9	7.9	7.9
	Min/Max	7.5/8.0	7.5/8.0	7.7/8.1	7.8/8.1	7.6/8.2
EC§(mmhos/cm)	Mean	1.1	1.1	2.3	2.2	2.9
	Min/Max	0.8/1.4	0.8/1.6	1.4/3.1	1.1/3.9	1.1/4.8
Saturation (%)	Mean	38	41	51	53	59
	Min/Max	32/46	34/52	43/59	39/60	47/78
SAR¶	Mean	0.4	0.6	1.0	0.9	4.3
	Min/Max	0.4/0.5	0.4/1.1	0.5/3.3	0.5/1.8	0.5/12.4

+12 replications per mean.

‡SL = sandy loam, SCL = sandy clay loam and CL = clay loam.

§Electrical conductivity.

¶Sodium adsorption ratio.

Table A5. Topsoil tillage effects with time on bulk density at Center and Coteau.

Data Year+	Tillage Treatment+	Profile Depth (m)§ 0-0.3	0.3-0.6	0-0.3	0.3-0.6
		(Mg/m³)			
		Center		Coteau	
1987C	CH	1.47	1.53	1.47	1.58
	DR	1.47	1.55	1.49	1.59
	GR	1.48	1.53	1.45	1.56
	LSD(0.10)¶	NS	0.01	0.02	0.01
1989R	CH	1.56	1.70	1.42	1.61
	DR	1.48	1.58	1.44	1.57
	GR	1.50	1.66	1.50	1.62
	LSD(0.10)	0.04	0.06	0.06	NS
1990P	CH	1.50	1.66	1.41	1.62
	DR	1.49	1.66	1.42	1.65
	GR	1.49	1.69	1.43	1.62
	LSD(0.10)	NS	NS	NS	NS
1990R	CH	1.43	1.69	1.36	1.57
	DR	1.44	1.59	1.22	1.55
	GR	1.39	1.68	1.40	1.59
	LSD(0.10)	NS	0.04	0.12	NS
1991P	CH	1.42	1.70	1.31	1.59
	DR	1.35	1.63	1.34	1.58
	GR	1.41	1.71	1.35	1.63
	LSD(0.10)	0.05	0.04	NS	NS
1991R	CH	1.38	1.70	1.36	1.60
	DR	1.33	1.65	1.35	1.58
	GR	1.34	1.71	1.38	1.62
	LSD(0.10)	NS	NS	NS	NS
1992P	CH	1.36	1.72	ND++	ND
	DR	1.34	1.61	ND	ND
	GR	1.34	1.66	ND	ND
	LSD(0.10)	NS	0.08	---	---
1992R	CH	1.56	1.77	ND	ND
	DR	1.50	1.69	ND	ND
	GR	1.50	1.72	ND	ND
	LSD(0.10)	NS	NS	---	---
Yr x Top	LSD(0.10)	NS	NS	0.07	NS

+C = access tube installation, P = penetrometer sampling spring, and R = root sampling fall.

+CH = chisel, DR = deep rip, and GR = grader rip.

§0.3-0.6 m depth averaged across subsoil tillage treatments.

¶Least significant difference at the P = 0.10 level. NS indicates no significant difference among mean values.

++Site discontinued in 1991 due to mining activities.

Table A6. Subsoil tillage effects with time on bulk density at Center and Coteau.

Date Year+	Tillage Treatment+	Profile Depth (m)§ 0.3-0.6	0.6-0.9	0.9-1.2	0.3-0.6	0.6-0.9	0.9-1.2
				(Mg/m³)			
			Center			Coteau	
1987C	CH	1.55	1.56	1.57	1.57	1.61	1.60
	DL	1.50	1.54	1.55	1.57	1.62	1.59
	DR	1.54	1.55	1.57	1.60	1.61	1.59
	GR	1.54	1.56	1.55	1.58	1.62	1.60
	NT	1.54	1.57	1.56	1.56	1.58	1.56
	LSD(0.10)¶	0.03	NS	NS	NS	NS	0.02
1989R	CH	1.67	ND++	ND	1.60	ND	ND
	DL	1.66	ND	ND	1.54	ND	ND
	DR	1.60	ND	ND	1.59	ND	ND
	GR	1.67	ND	ND	1.61	ND	ND
	NT	1.64	ND	ND	1.62	ND	ND
	LSD(0.10)	NS	---	---	NS	---	---
1990P	CH	1.68	ND	ND	1.57	1.55	1.62
	DL	1.62	1.47	1.66	1.64	1.57	1.59
	DR	1.64	1.52	1.84	1.66	1.69	1.57
	GR	1.70	1.86	1.80	1.62	1.65	1.67
	NT	1.71	1.60	1.82	1.64	1.69	1.80
	LSD(0.10)	NS	---	---	NS	NS	NS
1990R	CH	1.70	1.75	1.74	1.47	1.59	1.64
	DL	1.56	1.63	1.59	1.69	1.66	1.73
	DR	1.64	1.68	1.68	1.55	1.57	1.65
	GR	1.66	1.65	1.60	1.62	1.51	1.57
	NT	1.72	1.75	1.76	1.52	1.64	1.70
	LSD(0.10)	0.08	NS	NS	NS	NS	NS
1991P	CH	1.69	1.74	1.70	1.54	1.59	1.61
	DL	1.59	1.61	1.62	1.55	1.53	1.55
	DR	1.64	1.67	1.66	1.57	1.65	1.72
	GR	1.71	1.74	1.75	1.56	1.60	1.59
	NT	1.76	1.76	1.78	1.78	1.94	1.90
	LSD(0.10)	0.07	0.05	0.07	0.12	0.10	0.10
1991R	CH	1.72	ND	ND	1.58	1.56	1.78
	DL	1.62	1.62	1.73	1.63	1.51	1.52
	DR	1.62	1.67	1.60	1.64	1.67	ND
	GR	1.75	1.84	ND	1.52	1.58	ND
	NT	1.73	1.65	ND	1.63	1.67	ND
	LSD(0.10)	0.08	NS	---	NS	NS	---

Table A6 continued.

Date Year	Tillage Treatment	Profile Depth (m)[§] 0.3-0.6	0.6-0.9	0.9-1.2	0.3-0.6	0.6-0.9	0.9-1.2
				(Mg/m³)			
1992P	CH	1.70	1.80	1.78	ND	ND	ND
	DL	1.59	1.67	1.76	ND	ND	ND
	DR	1.66	1.61	1.71	ND	ND	ND
	GR	1.65	1.69	1.76	ND	ND	ND
	NT	1.72	1.66	1.81	ND	ND	ND
	LSD(0.10)	NS	NS	NS	---	---	---
1992R	CH	1.78	1.94	1.72	ND	ND	ND
	DL	1.65	1.62	1.55	ND	ND	ND
	DR	1.72	1.77	1.83	ND	ND	ND
	GR	1.69	1.62	1.77	ND	ND	ND
	NT	1.80	1.78	ND	ND	ND	ND
	LSD(0.10)	NS	NS	NS	---	---	---
Yr x Sub	LSD(0.10)	NS	0.10	NS	0.08	0.20	0.10

[†]C = access tube installation, P = penetrometer sampling, and R = root sampling.

[‡]CH = chisel, DL = deep lift, DR = deep rip, GR = grader rip, and NT = no till.

[§]Averaged across topsoil tillage treatments which may have penetrated one or more depth increments.

[¶]Least significant difference at the P = 0.10 level. NS indicates no significant difference among mean values. --- indicates insufficient data for analysis.

[††]No data. Coteau discontinued after 1991 due to mining activities.

Table A7. Yearly changes in bulk density measured at the Center and Coteau locations.

Year of Data+	Profile Depth (m) 0-0.3	0.3-0.6	0.6-0.9	0.9-1.2
		(Mg/m³)		
		Center Location		
1987C	1.47a‡	1.54a	1.56a	1.56a
1989R	1.52ab	1.65b	ND§	ND
1990P	1.49ac	1.67b	1.61a	1.75bcd
1990R	1.42d	1.66b	1.69b	1.67c
1991P	1.39de	1.68b	1.70b	1.70bc
1991R	1.35e	1.69b	1.69b	1.67bc
1992P	1.35e	1.66b	1.69b	1.76de
1992R	1.52bc	1.73c	1.69b	1.73be
		Coteau Location		
1987C	1.47a	1.58a	1.60ab	1.59a
1989R	1.45ab	1.60ab	ND	ND
1990P	1.42b	1.63b	1.62b	1.63ab
1990R	1.33c	1.57a	1.59ac	1.65bc
1991P	1.33c	1.60ab	1.66d	1.67cd
1991R	1.36c	1.60ab	1.60bc	1.65abd

+Core data from access tube installation (C), penetrometer measurements (P) and root measurements (R).

‡Values within locations and depths followed by the same letter are not significantly different at the P = 0.10 level.

§No data.

Table A8. Selected mean cone index values by tillage depths with time at the Center tillage location.

Year	Tillage+ Topsoil	Tillage+ Subsoil	Profile Depth (cm) 0-15	15-30	30-35+	35-50	50-65	65-100
						(MPa)		
						Year Effects		
1990			2.44A§	5.73A	6.74A	7.86A	9.06A	6.91A
1991			4.00B	7.73B	9.70B	12.73B	14.88B	13.60A
1992			3.72B	6.91B	8.70B	12.20B	13.03B	10.86A
						Year x Topsoil Tillage Effects		
1990	CH		2.20A	6.24A	8.03A	9.78A	10.01A	7.24AB
	DR		2.36A	4.87A	5.31A	6.04A	7.80A	7.00B
	GR		2.76A	6.06A	7.04A	8.16A	10.59A	6.08AB
		LSD(0.10)#	NS	NS	1.31	1.36	NS	---
1991	CH		3.86A	8.92A	12.14A	14.65A	14.46A	12.25A
	DR		3.56A	6.04A	6.78A	10.00A	12.76A	12.06A
	GR		4.63A	8.28A	10.39A	13.75A	17.82A	18.01C
		LSD(0.10)	0.73	1.70	2.60	2.40	NS	NS
1992	CH		4.07A	8.34A	11.71A	14.26A	13.97A	11.16A
	DR		3.46A	6.04A	6.43A	10.06A	12.29A	11.60A
	GR		3.64A	6.35A	8.16A	12.43A	13.05A	9.84A
		LSD(0.10)	NS	1.43	2.00	2.45	NS	NS
						Year x Subsoil Tillage Effects		
1990		CH	2.39A	4.93A	5.54A	8.62A	11.28A	ND++
		DL	2.49A	6.67A	7.38A	7.76AB	8.46A	8.29A
		DR	1.94A	4.93A	7.30A	8.05AB	8.51A	8.48A
		GR	2.58A	6.14A	7.22A	7.93AB	10.15A	8.54A
		NT	2.78A	5.96A	6.34A	6.96B	8.37A	5.94A
		LSD(0.10)	0.42	0.98	1.33	NS	NS	---
1991		CH	3.80A	7.40A	10.54A	13.97CDE	16.10A	15.87A
		DL	4.90A	7.14A	7.12A	8.80AB	11.56A	10.99A
		DR	3.37A	7.47A	10.39A	12.44DFG	15.98A	12.01A
		GR	3.76A	9.61A	11.43A	15.37C	15.27A	17.91A
		NT	4.16A	7.25A	9.41A	13.68CEF	18.17A	ND
		LSD(0.10)	0.79	NS	NS	NS	NS	NS

Table A8 continued.

Year	Tillage Topsoil	Tillage Subsoil	Profile Depth (cm) 0-15	15-30	30-35+	35-50	50-65	65-100
						(MPa)		
1992		CH	4.13A	7.66A	9.57A	14.34CF	14.54A	13.14A
		DL	3.03A	5.93A	6.81A	10.09AG	13.18A	12.02A
		DR	3.70A	7.20A	9.43A	12.84CD	12.47A	7.89A
		GR	3.25A	6.44A	7.97A	8.94AB	12.43A	9.89A
		NT	4.51A	7.32A	9.81A	15.03C	12.41A	11.92A
		LSD(0.10)	NS	NS	NS	2.03	NS	NS

+CH = chisel, DL = deep lift, DR = deep rip between shank tracks, GR = grader rip, and NT = no till.

+Transition zone between topsoil and subsoil.

§Values in columns by depth and effect followed by the same letter are not significantly different at the P = 0.10 level.

¶Least significant difference at the P = 0.10 level for within year values. NS indicates no significant difference among mean values. --- indicates not enough data points for the ANOVA model.

++No data.

Table A9. Selected mean cone index values by tillage depths with time at the Coteau tillage location.

Year	Tillage[+] Topsoil	Subsoil	Profile Depth (cm) 0-15	15-40	40-56[+]	56-73	73-85	85-100
					(MPa)			
					Year Effects			
1990			1.11A[δ]	3.92A	7.68A	8.74A	7.72A	7.54A
1991			2.25B	6.33B	9.79B	12.48B	12.97B	10.11B
					Year x Topsoil Tillage Effects			
1990	CH		1.02A	3.18A	7.48A	8.25A	7.31A	6.67A
	DR		1.01A	3.47A	7.24A	9.28A	8.48A	8.41A
	GR		1.29A	5.11A	8.33A	8.47A	7.31A	7.40A
		LSD(0.10)[#]	NS	0.90	NS	NS	NS	0.28
1991	CH		1.95A	5.48A	9.76A	12.40A	13.89A	10.46A
	DR		2.25A	5.58A	9.50A	12.60A	11.86A	10.47A
	GR		2.56A	7.93A	10.13A	12.43A	13.11A	9.49A
		LSD(0.10)	NS	1.24	NS	NS	NS	NS
					Year x Subsoil Tillage Effects			
1990		CH	1.09A	3.90A	6.74A	7.95A	7.86A	6.82A
		DL	1.11A	4.07A	9.03A	8.89A	6.41A	7.02A
		DR	0.96A	3.42A	7.58A	9.15A	7.16A	8.38A
		GR	1.11A	3.85A	7.17A	8.88A	9.18A	7.22A
		NT	1.26A	4.37A	7.70A	9.01A	7.34A	9.22A
		LSD(0.10)	NS	NS	NS	NS	NS	1.30
1991	CH		2.00A	5.95A	8.09A	10.79A	11.52A	9.00A
	DL		3.13A	8.09A	11.39A	11.84A	12.35A	9.64A
	DR		2.12A	5.91A	8.27A	12.53A	13.67A	11.60A
	GR		2.31A	6.59A	11.79A	13.75A	12.72A	9.66A
	NT		1.71A	5.12A	9.44A	13.76A	15.25A	11.70A
		LSD(0.10)	NS	1.72	2.05	NS	NS	NS

[+]CH = chisel, DL = deep lift, DR = deep rip between shank tracks, GR = grader rip, and NT = no till.

[+]Transition zone between topsoil and subsoil.

[δ]Values in columns followed by the same letter by depth and effect are not significantly different at the P = 0.10 level.

[#]Least significant difference at the P = 0.10 level for within year values. NS indicates no significant difference among mean values.

Table A10. Selected mean cone index values with time from the deep rip topsoil tillage treatment at the Center location.

Year	Topsoil Tillage†	Profile Depth (cm) 0-20	20-100
		(MPa)	
		Year Effects	
1990		2.86A‡	4.76A
1991		3.98B	6.75B
1992		3.94B	7.60C
		Shank vs Nonshank Effects	
	DR	3.66A	8.69A
	DRSH	3.52A	4.05B
		Year x Shank/Nonshank Effects	
1990	DR	2.88A	5.98A
	DRSH	2.83A	3.54B
	LSD(0.10)§	NS	1.51
1991	DR	4.05A	10.23C
	DRSH	3.92A	3.28B
	LSD(0.10)	NS	1.10
1992	DR	4.05A	9.87C
	DRSH	3.83A	5.33A
	LSD(0.10)	NS	1.49

†DR = between shank tracks and DRSH = within shank tracks.

‡Values within columns by depth and effect followed by the same letter are not significantly different at the P = 0.10 level.

§Least significant difference at the P = 0.10 level for within year values. NS indicates no significant difference between mean values.

Table A11. Selected mean cone index values from the deep rip topsoil tillage treatment with time at the Coteau location.

	Tillage[+]		Profile Depth (cm)		
Year	Topsoil	Subsoil	0-20	20-60	60-100
				(MPa)	
				Year Effects	
1990			1.24A[+]	4.81A	8.86A
1991			2.55B	7.10B	12.39B
				Year x Topsoil Tillage Effects	
1990	DR		1.19A	5.73A	9.24A
	DRSH		1.30A	3.89A	8.56A
		LSD(0.10)[δ]	NS	0.92	NS
1991	DR		2.71A	8.04A	12.58A
	DRSH		2.38A	6.16A	12.20A
		LSD(0.10)	NS	1.32	NS
				Year x Subsoil Tillage Effects	
1990		CH	1.45A	3.92A	8.16A
		DL	1.12A	4.78A	8.60A
		DR	1.06A	4.25A	9.05A
		GR	1.25A	5.44A	8.82A
		NT	1.33A	5.66A	10.45A
		LSD(0.10	NS	NS	NS
1991		CH	2.33A	5.30A	10.46A
		DL	3.15A	9.08A	12.85A
		DR	2.76A	6.69A	11.62A
		GR	2.78A	6.48A	11.54A
		NT	1.72A	7.93A	17.01A
		LSD(0.10)	NS	NS	NS

[+]DR = deep rip between shank tracks, DRSH = deep rip within shank, CH = chisel tracks, DL = deep lift, GR = grader rip, and NT = no till.

[+]Values in columns by depth and effect followed by the same letter are not significantly different at the P = 0.10 level.

[δ]Least significant difference at the P = 0.10 level for within year values. NS indicates no significant difference among mean values.

Table A12. Mean volumetric soil water percent for cone index cores at the Center and Coteau locations.+

Year		Profile Depth (cm)						
		0-15	15-30	30-45	45-60	60-75	75-90	90-105
					(%)			
					Center Location			
1990		11.8	11.7	11.0	12.8	10.6	12.8	15.1
1991		8.8	11.0	10.8	12.3	12.3	12.6	12.9
1992		8.0	11.2	11.6	13.2	14.7	14.9	15.7
	LSD(0.10)‡	1.4	0.4	NS	NS	NS	NS	0.5
					Coteau Location			
1990		19.0	20.1	15.1	14.0	14.0	15.9	17.0
1991		13.5	14.3	14.2	13.2	13.8	14.9	17.9
	LSD(0.10)	1.6	0.3	0.3	NS	NS	NS	NS

+Averaged over tillage treatments.

‡Least significant differences at the P = 0.10 level. NS indicates no significant difference among mean values.

Table A13. Tillage influences on yearly forage yields at the Center and Coteau locations.

Tillage Treatment[+]			Location/Year of Data				
			Center			Coteau	
Topsoil	Subsoil		1990	1991	1992	1990	1991
					(Mg/ha)		
CH			1.16	2.36	2.25	1.87	2.38
DR			1.05	2.19	1.94	2.09	2.37
GR			1.24	2.52	2.17	1.79	2.34
		LSD(0.10)[+]	NS	0.23	NS	NS	NS
	CH		0.99	2.56	2.33	1.83	2.45
	DL		1.37	2.15	2.02	2.14	2.07
	DR		1.34	2.43	2.26	2.22	2.56
	GR		1.21	2.33	2.03	1.75	2.36
	NT		0.83	2.30	1.96	1.64	2.38
		LSD(0.10)	NS	NS	NS	0.30	NS
CH	CH		0.89	2.11	2.13	1.90	2.52
	DL		1.37	2.30	2.41	1.64	2.08
	DR		1.08	2.33	2.14	2.21	2.58
	GR		1.72	2.75	2.28	1.98	2.33
	NT		0.72	2.30	2.30	1.62	2.38
DR	CH		0.69	2.40	2.18	1.79	2.53
	DL		1.17	1.87	1.51	2.95	2.24
	DR		1.76	2.49	2.55	2.45	2.47
	GR		0.88	2.04	1.96	1.74	2.44
	NT		0.75	2.14	1.49	1.53	2.18
GR	CH		1.40	3.16	2.68	1.80	2.31
	DL		1.58	2.28	2.13	1.83	1.90
	DR		1.17	2.46	2.08	1.99	2.62
	GR		1.04	2.20	1.86	1.52	2.30
	NT		1.03	2.48	2.10	1.78	2.56
		LSD(0.10)	NS	0.52	NS	NS	NS

[+]CH = chisel, DL = deep lift, DR = deep rip, GR = grader rip, and NT = no till.

[+]Least significant difference at the P = 0.10 level. NS indicates no significant difference among mean values.

Table A14. Deep rip topsoil tillage influences on yearly forage yields at the Center and Coteau locations.

Tillage Treatment+			Location/Year of Data				
			Center			Coteau	
Topsoil	Subsoil		1990	1991	1992	1990	1991
					(Mg/ha)		
DR			1.05	2.19	1.94	2.09	2.37
DRSH			1.09	2.11	1.90	1.83	2.22
		LSD(0.10)	NS	NS	NS	0.19	NS
	CH		0.87	2.22	2.27	1.78	2.36
	DL		1.13	1.94	1.58	2.44	2.13
	DR		1.71	2.35	2.37	2.31	2.47
	GR		0.88	2.13	1.88	1.62	2.28
	NT		0.76	2.09	1.39	1.64	2.24
		LSD(0.10)	0.37	NS	0.30	NS	NS
DR	CH		0.69	2.40	2.18	1.79	2.53
	DL		1.17	1.87	1.51	2.95	2.24
	DR		1.76	2.49	2.55	2.45	2.47
	GR		0.88	2.04	1.96	1.74	2.44
	NT		0.75	2.14	1.49	1.53	2.18
DRSH	CH		1.05	2.04	2.36	1.78	2.18
	DL		1.09	2.02	1.66	1.94	2.02
	DR		1.66	2.22	2.19	2.16	2.47
	GR		0.89	2.22	1.99	1.51	2.13
	NT		0.77	2.03	1.30	1.76	2.31
	NT	LSD(0.10)	NS	NS	NS	0.42	NS

+CH = chisel, DL = deep lift, DR = deep rip, DRSH = deep rip shank track, grader rip, and NT = no till.

+Least significant difference at the P = 0.10 level. NS indicates no significant difference among mean values.

Table A15. Selected mean forage yields with time at Center and Coteau.

Year	Tillage Treatment+ Topsoil	Subsoil		Location Center	Coteau
				(Mg/ha)	
				No DRSH Data	
1990				1.15	1.92
1991				2.35	2.36
1992				2.12	----
			LSD(0.10)+	0.18	0.27
	CH			1.92	2.12
	DR			1.72	2.33
	GR			1.98	2.06
			LSD(0.10)	0.16	NS
		CH		1.96	2.14
		DL		1.85	2.10
		DR		2.01	2.39
		GR		1.86	2.05
		NT		1.70	2.01
			LSD(0.10)	NS	0.20
				Topsoil DR vs DRSH Data	
1990				1.07	1.96
1991				2.15	2.30
1992				1.92	----
			LSD(0.10)	0.19	NS
	DR			1.72	2.23
	DRSH			1.70	2.03
			LSD(0.10)	NS	0.12
		CH		1.79	2.07
		DL		1.55	2.29
		DR		2.14	2.39
		GR		1.66	1.95
		NT		1.41	1.94
			LSD(0.10)	0.21	NS

+CH = chisel, DL = deep lift, DR = deep rip between shank tracks, DRSH = deep rip shank track, GR = grader rip, and NT = no tillage.

+Least significant difference at the P = 0.10 level. NS indicates no significant difference among mean values.

Table A16. Mean alfalfa root length density by years as influenced by topsoil tillage treatments at the two topsoil/subsoil tillage locations.†

		Profile Depth (cm)									
Year	Topsoil Tillage	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
						(cm/cm³ x 10)					
						Center Location					
1989	Chisel (CH)	19.8	11.8	7.1	0.6						
	Deep Rip (DR)	20.5	9.2	3.8	0.9						
	Grader Rip (GR)	21.9	12.4	8.3	0.0						
	LSD(0.10)‡	NS	NS	NS	NS						
1990	CH	24.7	13.4	5.9	1.2	0.6					
	DR	23.5	13.3	6.1	2.5	0.4					
	GR	24.2	14.7	5.6	0.6	0.3					
	LSD(0.10)	NS	NS	NS	NS	NS					
1991	CH	44.9	29.2	11.1	5.1	0.8	0.4	0.5	1.6		
	DR	39.8	19.7	14.2	4.5	0.8	0.7	0.3	0.1		
	GR	43.6	27.8	13.8	4.7	1.2	0.1	0.1	0.2		
	LSD(0.10)	NS	5.0	NS	NS	NS	0.4	NS	0.2		
1992	CH	86.6	51.3	31.7	5.8	3.0	3.7	3.9	1.1	13.6	0.0
	DR	81.9	55.7	30.4	7.2	6.0	1.7	4.1	5.0	3.2	0.0
	GR	92.4	46.8	35.5	12.4	3.6	0.3	0.2	1.3	2.0	7.6
	LSD(0.10)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
						Coteau Location					
1989	CH	31.5	19.8	10.8	9.2						
	DR	24.4	12.5	9.0	2.3						
	GR	26.6	21.9	7.1	1.0						
	LSD(0.10)	NS	NS	NS	3.4						
1990	CH	29.8	16.4	7.0	3.4	1.3					
	DR	28.8	17.4	9.3	3.4	1.6					
	GR	28.9	15.4	7.4	2.8	0.0					
	LSD(0.10)	NS	NS	NS	NS	NS					
1991	CH	49.5	27.9	15.1	8.3	4.0	2.1	0.0	0.0		
	DR	53.2	30.9	22.4	5.6	4.9	2.5	0.4	0.8		
	GR	66.2	33.8	14.3	6.6	1.7	0.0	0.0	0.0		
	LSD(0.10)	12.0	NS	NS	NS	NS	NS	NS	NS		

†Blanks indicate no roots found for those depth increments.

‡Least significant difference at the P = 0.10 level. NS indicates no significant differences among mean values.

Table A17. Mean alfalfa root length density by years as influenced by subsoil tillage treatments at the two topsoil/subsoil tillage locations.†

Year	Subsoil Tillage	Profile Depth (cm)									
		5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
							(cm/cm³ x10)				
							Center Location				
1989	Chisel (CH)	19.1	10.3	4.2	0.5						
	Deep Lift (DL)	20.8	12.2	5.9	0.6						
	Deep Rip (DR)	24.4	12.9	10.2	0.0						
	Grader Rip (GR)	21.1	11.4	6.3	0.9						
	No Till (NT)	18.6	11.0	9.7	0.0						
	LSD(0.10)‡	NS	NS	NS	0.3						
1990	CH	24.1	15.5	5.2	1.7	0.3					
	DL	18.5	12.2	5.3	1.3	0.8					
	DR	27.5	12.7	6.2	1.8	0.4					
	GR	23.1	13.5	6.0	1.1	0.7					
	NT	27.6	15.6	6.8	1.2	0.0					
	LSD(0.10)	NS	NS	NS	NS	NS					
1991	CH	42.8	21.6	10.9	3.8	0.0	0.0	0.0	0.0		
	DL	39.0	18.3	15.4	5.3	2.4	1.2	0.8	2.6		
	DR	34.2	24.2	9.8	2.8	1.0	0.7	0.5	0.4		
	GR	54.7	33.8	13.2	4.9	0.8	<0.1	0.0	0.0		
	NT	43.2	30.2	15.7	7.1	0.4	0.0	0.0	0.0		
	LSD(0.10)	NS	NS	NS	NS	NS	0.4	0.5	0.4		
1992	CH	88.3	46.8	27.5	8.5	2.6	0.2	0.8	1.3	0.0	0.0
	DL	58.3	35.0	27.6	5.8	4.0	1.1	2.2	1.4	0.0	0.0
	DR	91.8	53.0	26.2	4.8	5.6	6.4	7.4	3.0	7.2	7.6
	GR	76.8	47.1	32.3	8.6	8.8	1.8	3.3	6.4	7.1	0.0
	NT	123.8	74.7	49.2	14.6	0.0	0.0	0.0	0.0	0.0	0.0
	LSD(0.10)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
							Coteau Location				
1989	CH	23.7	19.9	10.0	13.1						
	DL	35.4	22.0	4.5	2.8						
	DR	27.3	21.5	13.9	3.2						
	GR	29.9	20.6	8.0	3.0						
	NT	26.0	15.7	8.6	3.0						
	LSD(0.10)	NS	NS	NS	5.1						

Table A 17 continued.

		Profile Depth (cm)									
Year	Subsoil Tillage	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
1990	CH	29.7	18.2	9.4	3.2	0.8					
	DL	29.2	13.8	6.0	0.2	0.0					
	DR	34.2	19.9	7.1	5.7	0.8					
	GR	30.0	15.9	7.9	3.0	1.3					
	NT	22.8	14.2	9.1	4.0	1.9					
	LSD(0.10)	NS	NS	NS	NS	NS					
1991	CH	61.2	30.8	23.4	6.5	6.8	2.7	0.6	1.3		
	DL	51.3	28.8	16.7	3.1	0.5	0.0	0.0	0.0		
	DR	46.4	41.0	17.4	9.8	3.9	0.0	0.0	0.0		
	GR	78.8	29.0	14.4	7.1	4.9	4.9	0.0	0.0		
	NT	43.8	25.6	17.4	7.6	1.5	0.0	0.0	0.0		
	LSD(0.10)	NS	NS	NS	NS	2.0	NS	NS	NS		

†Blanks indicate no roots found for these depth increments.

‡Least significant difference at the P = 0.10 level. NS indicates no significant difference among mean values.

Table A18. Mean alfalfa root mass by years as influenced by topsoil tillage treatments at the two topsoil/subsoil tillage locations.†

		Profile Depth (cm)									
Year	Topsoil Tillage	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
		(g x 10)									
		Center Location									
1989	Chisel (CH)	3.2	1.2	0.3	<0.1						
	Deep Rip (DR)	2.7	1.1	0.2	<0.1						
	Grader Rip (GR)	3.5	1.9	0.5	0.0						
	LSD(0.10)‡	NS	NS	0.2	NS						
1990	CH	7.9	4.2	1.0	0.1	<0.1					
	DR	5.8	2.4	0.9	0.2	<0.1					
	GR	8.7	3.6	0.8	0.1	<0.1					
	LSD(0.10)	NS	NS	NS	NS	NS					
1991	CH	21.5	12.6	2.5	0.3	<0.1	<0.1	<0.1	<0.1		
	DR	18.0	7.0	2.4	0.4	<0.1	0.1	0.1	<0.1		
	GR	17.6	9.1	2.9	0.6	0.1	<0.1	<0.1	<0.1		
	LSD(0.10)	NS	NS	NS	NS	NS	NS	NS	NS		
1992	CH	24.9	13.0	3.0	0.6	0.2	0.5	0.7	0.1	0.4	0.0
	DR	20.8	12.8	7.4	1.1	0.7	1.3	1.3	0.2	0.1	0.0
	GR	33.9	16.0	3.4	0.5	0.3	<0.1	<0.1	0.1	0.8	0.3
	LSD(0.10)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		Coteau Location									
1989	CH	4.0	2.2	0.9	0.4						
	DR	4.4	2.6	0.4	0.1						
	GR	3.3	1.2	0.3	<0.1						
	LSD(0.10)	NS	0.8	0.5	0.3						
1990	CH	16.3	7.8	1.6	0.7	0.2					
	DR	19.4	8.4	2.2	0.3	0.1					
	GR	12.2	4.5	0.7	0.2	0.0					
	LSD(0.10)	NS	NS	NS	0.3	NS					
1991	CH	29.1	9.8	3.2	0.7	0.2	<0.1	0.0	0.0		
	DR	32.9	15.8	4.2	1.1	0.3	0.2	<0.1	<0.1		
	GR	34.5	8.0	1.3	0.5	0.1	0.0	0.0	0.0		
	LSD(0.10)	NS	6.0	NS	NS	NS	NS	NS	NS		

†Blanks indicate no roots found for those depth increments.

‡Least significant difference at the P = 0.10 level. NS indicates no significant differences among mean values.

Table A19. Mean alfalfa root mass by years as influenced by subsoil tillage treatment at the two topsoil/subsoil tillage locations.†

		Profile Depth (cm)									
Year	Subsoil Tillage	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
							(g x 10)				
							Center Location				
1989	Chisel (CH)	2.2	1.1	0.2	<0.1						
	Deep Lift (DL)	3.3	1.5	0.3	<0.1						
	Deep Rip (DR)	3.7	1.8	0.7	0.0						
	Grader Rip (GR)	3.2	1.1	0.3	<0.1						
	No Till (NT)	3.8	1.9	0.4	0.0						
	LSD(0.10)‡	NS	NS	NS	NS						
1990	CH	10.6	5.4	1.2	0.1	<0.1					
	DL	6.2	3.0	0.7	0.1	<0.1					
	DR	5.6	3.8	1.2	0.2	<0.1					
	GR	6.0	2.3	0.6	0.1	<0.1					
	NT	8.9	2.2	0.8	0.1	0.0					
	LSD(0.10)	NS	NS	NS	NS	NS					
1991	CH	16.6	7.4	2.1	0.5	0.0	0.0	0.0	0.0		
	DL	12.5	4.1	2.4	0.3	0.2	<0.1	<0.1	<0.1		
	DR	21.5	13.1	2.1	0.3	<0.1	0.1	0.1	<0.1		
	GR	15.4	8.2	3.0	0.4	<0.1	<0.1	0.0	0.0		
	NT	29.1	15.1	3.4	0.6	<0.1	0.0	0.0	0.0		
	LSD(0.10)	NS	NS	NS	NS	NS	NS	NS	NS		
1992	CH	22.4	14.8	2.8	0.6	0.1	<0.1	1.6	0.1	0.0	0.0
	DL	12.3	6.4	3.6	1.6	0.3	0.1	0.1	0.1	0.0	0.0
	DR	35.6	17.3	3.6	0.2	1.1	2.8	1.6	0.3	0.5	0.3
	GR	19.2	12.0	7.9	0.5	0.6	0.1	0.1	0.2	0.2	0.0
	NT	44.5	19.3	5.2	0.6	0.0	0.0	0.0	0.0	0.0	0.0
	LSD(0.10)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
							Coteau Location				
1989	CH	4.1	2.3	0.6	0.4						
	DL	1.9	0.8	0.2	0.1						
	DR	2.9	1.7	0.5	0.1						
	GR	4.5	2.1	0.5	0.1						
	NT	5.5	2.2	1.2	0.3						
	LSD(0.10)	1.7	NS	NS	NS						

Table A19 continued.

Year	Subsoil Tillage	Profile Depth (cm)									
		5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120	120-135	135-150
1990	CH	19.6	8.1	1.5	0.3	0.1					
	DL	14.7	4.9	0.7	<0.1	0.0					
	DR	17.9	8.5	1.9	1.1	0.2					
	GR	15.3	6.5	1.6	0.3	0.1					
	NT	12.6	6.4	1.8	0.4	0.1					
	LSD(0.10)	NS	NS	NS	0.4	NS					
1991	CH	50.2	13.8	2.3	0.6	0.5	0.2	0.1	0.1		
	DL	29.5	9.6	3.4	0.2	<0.1	0.0	0.0	0.0		
	DR	24.2	7.6	2.8	1.2	0.2	0.0	0.0	0.0		
	GR	25.7	11.0	2.7	0.8	0.3	0.2	0.0	0.0		
	NT	29.6	13.9	3.4	1.2	0.1	0.0	0.0	0.0		
	LSD(0.10)	NS	NS	NS	NS	0.2	NS	NS	NS		

†Blanks indicate no roots found for those depth increments.

†Least significant difference at the P = 0.10 level. NS indicates no significant difference among mean values.

Table A20. Mean soil bulk densities obtained from access tube installation at the Glenharold tillage location (spring, 1989).

Tillage	Crop	Depth (m)				
		0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5
				(Mg m^{-3})		
Chisel	Alfalfa	1.26	1.28	1.42	1.48	1.51
	Native Mix	1.26	1.30	1.42	1.58	1.67
	Precrop Mix	1.16	1.43	1.42	1.67	1.64
	Pubescent Wheatgrass	1.10	1.46	1.40	1.60	1.62
	Small Grain	1.20	1.41	1.40	1.56	1.58
	Tall Wheatgrass	1.34	1.54	1.50	1.55	1.52
Subsoil	Alfalfa	1.16	1.18	1.50	1.58	1.59
	Native Mix	1.18	1.38	1.35	1.40	1.58
	Precrop Mix	1.18	1.35	1.28	1.59	1.54
	Pubescent Wheatgrass	1.12	1.38	1.48	1.52	1.40
	Small Grain	1.11	1.16	1.46	1.64	1.52
	Tall Wheatgrass	1.24	1.28	1.46	1.56	1.62

Table A21. Mean soil bulk densities obtained from access tube installation at the Knife River tillage location (spring, 1989).

Tillage	Crop	Depth (m)				
		0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5
				(Mg m^{-3})		
Chisel	Alfalfa	1.49	1.66	1.56	1.75	1.82
	Native Mix	1.59	1.80	1.49	1.64	1.62
	Precrop Mix	1.44	1.72	1.50	1.76	1.69
	Pubescent Wheatgrass	1.42	1.72	1.67	1.80	1.80
	Small Grain	1.58	1.68	1.46	1.43	1.29
	Tall Wheatgrass	1.42	1.81	1.77	1.76	1.62
Subsoil	Alfalfa	1.44	1.28	1.78	1.60	1.78
	Native Mix	1.37	1.68	1.39	1.40	1.71
	Precrop Mix	1.50	1.70	1.60	1.59	1.58
	Pubescent Wheatgrass	1.56	1.44	1.42	1.72	1.62
	Small Grain	1.56	1.61	1.58	1.62	1.70
	Tall Wheatgrass	1.44	1.64	1.62	1.52	1.76

Table A22. Mean soil bulk densities obtained from the Glenharold tillage location.

Year	Tillage	Crop	0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5
					(Mg m^{-3})		
1989	Chisel	Alfalfa	1.26	1.28	1.42	1.48	1.51
		Native Mix	1.26	1.30	1.42	1.58	1.67
		Precrop Mix	1.16	1.43	1.42	1.67	1.64
		Pubescent Wheatgrass	1.10	1.46	1.40	1.60	1.62
		Small Grain	1.20	1.41	1.40	1.56	1.58
		Tall Wheatgrass	1.34	1.54	1.50	1.55	1.52
	Subsoil	Alfalfa	1.16	1.18	1.50	1.58	1.59
		Native Mix	1.18	1.38	1.35	1.40	1.58
		Precrop mix	1.18	1.35	1.28	1.59	1.54
		Pubescent Wheatgrass	1.12	1.38	1.48	1.52	1.40
		Small Grain	1.11	1.16	1.46	1.64	1.52
		Tall Wheatgrass	1.24	1.28	1.46	1.56	1.62
1990	Chisel	Alfalfa	1.73	1.74	1.58	1.85	
		Native Mix	1.74	1.72	1.72	1.82	
		Precrop Mix	1.70	1.69	1.67	1.87	
		Pubescent Wheatgrass	1.73	1.69	1.76	1.71	
		Small Grain	1.65	1.80	1.78	1.82	
		Tall Wheatgrass	1.78	1.74	1.77	1.81	
	Subsoil	Alfalfa	1.66	1.70	1.68	1.67	
		Native mix	1.69	1.72	1.76	1.91	
		Precrop Mix	1.63	1.69	1.67	1.78	
		Pubescent Wheatgrass	1.59	1.70	1.75	1.81	
		Small Grain	1.59	1.68	1.82	1.80	
		Tall Wheatgrass	1.60	1.69	1.78	1.80	
1991	Chisel	Alfalfa	1.47	1.65	1.64	1.66	
		Native Mix	1.47	1.66	1.61	1.64	
		Precrop Mix	1.49	1.62	1.65	1.39	
		Pubescent Wheatgrass	1.43	1.62	1.63	1.68	
		Small Grain	1.36	1.68	1.66	1.69	
		Tall Wheatgrass	1.53	1.63	1.60	1.79	
	Subsoil	Alfalfa	1.48	1.67	1.55	1.57	
		Native Mix	1.46	1.55	1.57	1.59	
		Precrop Mix	1.49	1.56	1.67	1.69	
		Pubescent Wheatgrass	1.48	1.64	1.65	1.58	
		Small Grain	1.42	1.55	1.65	1.64	
		Tall Wheatgrass	1.36	1.49	1.59	1.71	

Table A22 (continued).

Year	Tillage	Crop	Profile Depth (m)				
			0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5
			(Mg m^{-3})				
1992	Chisel	Alfalfa	1.52	1.84	1.53	1.69	
		Native Mix	1.46	1.76	1.58	1.58	
		Precrop mix	1.62	1.80	1.61	1.56	
		Pubescent Wheatgrass	1.47	1.76	1.67	1.84	
		Small Grain	1.51	1.75	1.69	1.87	
		Tall Wheatgrass	1.57	1.60	1.62	1.86	
	Subsoil	Alfalfa	1.44	1.73	1.82	1.96	
		Native Mix	1.39	1.67	1.71	1.87	
		Precrop Mix	1.66	1.85	1.76	1.81	
		Pubescent Wheatgrass	1.51	1.68	1.75	1.90	
		Small Grain	1.50	1.84	1.83	1.76	
		Tall Wheatgrass	1.63	1.73	1.91	1.95	

Table A23. Mean soil bulk densities obtained from the Knife River tillage location.

Year	Tillage	Crop	Depth (m) 0-0.3	0.3-0.6	0.6-0.9	0.9-1.2
			(Mg m^{-3})			
1989	Chisel	Alfalfa	1.49	1.67	1.56	1.75
		Native Mix	1.59	1.80	1.49	1.55
		Precrop Mix	1.50	1.70	1.55	1.76
		Pubescent Wheatgrass	1.42	1.72	1.67	1.79
		Small Grain	1.58	1.68	1.46	1.43
		Tall Wheatgrass	1.43	1.81	1.77	1.77
	Subsoil	Alfalfa	1.45	1.27	1.78	1.60
		Native Mix	1.37	1.68	1.39	1.40
		Precrop mix	1.43	1.73	1.55	1.59
		Pubescent Wheatgrass	1.56	1.44	1.42	1.72
		Small Grain	1.56	1.61	1.57	1.62
		Tall Wheatgrass	1.44	1.64	1.62	1.52
1990	Chisel	Alfalfa	1.73	1.74	1.58	1.85
		Native Mix	1.74	1.72	1.72	1.82
		Precrop Mix	1.70	1.69	1.67	1.87
		Pubescent Wheatgrass	1.73	1.69	1.76	1.71
		Small Grain	1.65	1.80	1.78	1.82
		Tall Wheatgrass	1.78	1.74	1.77	1.81
	Subsoil	Alfalfa	1.66	1.70	1.68	1.67
		Native mix	1.69	1.72	1.76	1.91
		Precrop Mix	1.63	1.69	1.67	1.78
		Pubescent Wheatgrass	1.59	1.70	1.75	1.81
		Small Grain	1.59	1.68	1.82	1.80
		Tall Wheatgrass	1.60	1.69	1.78	1.80
1991	Chisel	Alfalfa	1.47	1.65	1.64	1.66
		Native Mix	1.47	1.66	1.61	1.64
		Precrop Mix	1.49	1.62	1.65	1.39
		Pubescent Wheatgrass	1.43	1.62	1.63	1.68
		Small Grain	1.36	1.68	1.66	1.69
		Tall Wheatgrass	1.53	1.63	1.60	1.79
	Subsoil	Alfalfa	1.48	1.67	1.55	1.57
		Native Mix	1.46	1.55	1.57	1.59
		Precrop Mix	1.49	1.56	1.67	1.69
		Pubescent Wheatgrass	1.48	1.64	1.65	1.58
		Small Grain	1.42	1.55	1.65	1.64
		Tall Wheatgrass	1.36	1.49	1.59	1.71

Table A23 (continued)

Year	Tillage	Crop	Profile Depth (m) 0-0.3	0.3-0.6	0.6-0.9	0.9-1.2
			(Mg m^{-3})			
1992	Chisel	Alfalfa	1.52	1.84	1.53	1.69
		Native Mix	1.46	1.76	1.58	1.58
		Precrop mix	1.62	1.80	1.61	1.56
		Pubescent Wheatgrass	1.47	1.76	1.67	1.84
		Small Grain	1.51	1.75	1.69	1.87
		Tall Wheatgrass	1.57	1.60	1.62	1.86
	Subsoil	Alfalfa	1.44	1.73	1.82	1.96
		Native Mix	1.39	1.67	1.71	1.87
		Precrop Mix	1.66	1.85	1.76	1.81
		Pubescent Wheatgrass	1.51	1.68	1.75	1.90
		Small Grain	1.50	1.84	1.83	1.76
		Tall Wheatgrass	1.63	1.73	1.91	1.95

Table A24. Selected mean cone indices from the Glenharold tillage location.

Year	Tillage	Crop	Depth (m) 0.05	0.25	0.45	0.65	0.85
					(MPa)		
1990	Chisel	Alfalfa	0.56	4.20	6.40	5.28	5.34
		Native Mix	0.86	3.50	4.51	5.62	6.24
		Precrop Mix	0.50	3.14	4.65	5.92	4.75
		Pubescent Wheatgrass	0.48	3.33	3.43	5.58	6.10
		Small Grain	0.29	2.97	6.01	6.17	5.37
		Tall Wheatgrass	0.69	5.08	4.60	3.20	7.14
	Subsoil	Alfalfa	0.40	4.33	4.36	5.90	4.87
		Native Mix	0.42	1.45	1.64	4.13	4.83
		Precrop Mix	0.59	3.09	4.42	4.07	4.41
		Pubescent Wheatgrass	0.61	2.87	1.95	4.50	5.09
		Small Grain	0.45	2.41	2.89	4.33	4.66
		Tall Wheatgrass	0.52	2.33	4.02	4.48	5.24
1991	Chisel	Alfalfa	2.06	4.22	4.62	5.51	7.05
		Native Mix	0.84	1.77	5.34	5.24	4.81
		Precrop Mix	1.19	2.05	5.29	5.44	4.51
		Pubescent Wheatgrass	1.12	4.08	7.01	6.36	8.59
		Small Grain	0.58	1.98	3.33	4.28	5.28
		Tall Wheatgrass	0.86	3.44	4.34	7.14	5.02
	Subsoil	Alfalfa	0.87	2.86	1.28	9.76	8.11
		Native Mix	1.12	1.39	1.61	4.91	6.20
		Precrop Mix	1.13	1.88	2.60	6.46	5.85
		Pubescent Wheatgrass	0.84	1.77	1.74	4.44	5.89
		Small Grain	0.52	1.57	3.56	3.29	4.83
		Tall Wheatgrass	0.90	1.93	3.77	6.81	6.90
1992	Chisel	Alfalfa	1.76	6.19	5.84	7.01	8.07
		Native Mix	1.89	5.82	7.14	8.30	11.40
		Precrop Mix	1.96	5.91	6.39	6.36	11.32
		Pubescent Wheatgrass	1.74	5.26	6.61	6.55	8.98
		Small Grain	0.50	1.01	2.67	3.78	3.82
		Tall Wheatgrass	1.58	4.50	5.62	6.33	7.12
	Subsoil	Alfalfa	0.64	1.18	1.37	7.41	7.71
		Native Mix	0.95	3.47	4.36	7.54	7.54
		Precrop Mix	2.80	4.55	7.30	7.69	9.88
		Pubescent Wheatgrass	1.60	3.02	5.85	7.67	6.47
		Small Grain	0.41	0.69	2.40	4.56	5.70
		Tall Wheatgrass	0.40	2.56	6.70	7.59	8.18

Table A25. Selected mean cone indices from the Knife River tillage location.

Year	Tillage	Crop	Depth (m) 0.05	0.25	0.45	0.65	0.85
					(MPa)		
1990	Chisel	Alfalfa	0.90	11.30	8.68	5.85	2.90
		Native Mix	1.52	6.92	4.78	2.18	2.93
		Precrop Mix	0.85	10.51	10.71	5.74	6.38
		Pubescent Wheatgrass	0.76	9.81	6.39	2.93	3.64
		Small Grain	0.34	3.65	4.59	3.32	3.59
		Tall Wheatgrass	0.72	9.43	6.37	2.31	3.18
	Subsoil	Alfalfa	0.68	5.90	6.21	9.80	7.93
		Native Mix	0.68	4.31	2.18	2.17	2.12
		Precrop Mix	0.68	4.51	5.68	6.46	7.63
		Pubescent Wheatgrass	0.97	6.05	4.83	3.24	2.98
		Small Grain	0.42	3.10	2.76	4.01	3.62
		Tall Wheatgrass	1.41	6.47	4.98	3.81	4.23
1991	Chisel	Alfalfa	0.87	11.60	13.36	----	----
		Native Mix	1.69	8.81	7.79	6.93	5.25
		Precrop Mix	1.90	9.93	9.75	9.51	----
		Pubescent Wheatgrass	1.16	8.98	9.86	8.11	10.03
		Small Grain	0.68	4.21	3.61	5.10	4.90
		Tall Wheatgrass	1.36	9.20	6.97	7.07	6.35
	Subsoil	Alfalfa	1.47	7.97	7.48	10.39	5.08
		Native Mix	1.27	5.94	2.52	5.92	3.80
		Precrop Mix	0.90	7.54	6.32	7.87	6.59
		Pubescent Wheatgrass	2.11	7.34	8.58	8.25	6.76
		Small Grain	0.61	2.32	1.67	4.74	4.67
		Tall Wheatgrass	0.89	5.45	5.44	6.67	6.15
1992	Chisel	Alfalfa	1.17	10.27	10.74	13.90	6.74
		Native Mix	1.74	10.62	10.59	6.21	7.97
		Precrop Mix	2.43	15.15	11.48	13.47	14.21
		Pubescent Wheatgrass	1.55	12.43	13.37	6.12	11.33
		Small Grain	0.78	2.77	3.59	2.87	3.97
		Tall Wheatgrass	2.05	11.55	8.89	8.67	5.69
	Subsoil	Alfalfa	1.31	4.58	10.50	7.07	7.62
		Native Mix	2.04	7.46	9.83	6.22	7.31
		Precrop Mix	3.84	7.12	6.92	7.18	11.82
		Pubescent Wheatgrass	2.23	7.59	10.19	7.67	9.04
		Small Grain	0.57	1.42	2.12	3.26	2.95
		Tall Wheatgrass	1.91	9.73	10.69	3.60	2.61

Table A26. Mean wheat yields from the Glenharold and Knife River tillage locations..

Tillage	Year			
	1989	1990	1991	1992
		($Mg\ ha^{-1}$)		
		Glenharold		
Chisel	0.11	1.32	1.44	1.33
Subsoil	0.10	1.21	1.41	1.25
		Knife River		
Chisel	0.19	0.74	1.05	1.48
Subsoil	0.73	0.86	1.18	1.49

Table A27. Mean 1992 wheat yields obtained from the prior cropping experimental plots at the Glenharold and Knife River tillage location.

Tillage	Prior Crop	Glenharold	Knife River
		($Mg\ ha^{-1}$)	
Chisel	Alfalfa	1.39	0.97
	Native Mix	1.43	1.43
	Precrop Mix	1.32	0.96
	Pubescent Wheatgrass	1.38	1.09
	Small Grain	1.33	1.49
	Tall Wheatgrass	1.37	1.14
Subsoil	Alfalfa	1.41	0.90
	Native Mix	1.82	1.15
	Precrop Mix	1.64	0.88
	Pubescent Wheatgrass	1.50	1.23
	Small Grain	1.25	1.49
	Tall Wheatgrass	1.35	1.31

Table A28 . Mean forage yields from the Glenharold tillage location.

Year	Tillage	Crop	Yield
			(Mg ha^{-1})
1990	Chisel	Alfalfa	1.91
		Native Mix	1.32
		Precrop Mix	1.82
		Pub. Wheatgrass	2.91
		Tall Wheatgrass	1.09
	Subsoil	Alfalfa	2.00
		Native Mix	2.52
		Precrop Mix	2.55
		Pub. Wheatgrass	2.69
		Tall Wheatgrass	0.81
1991	Chisel	Alfalfa	2.35
		Native Mix	2.56
		Precrop Mix	4.22
		Pub. Wheatgrass	4.54
		Tall Wheatgrass	2.38
	Subsoil	Alfalfa	2.49
		Native Mix	3.10
		Precrop Mix	3.76
		Pub. Wheatgrass	5.02
		Tall Wheatgrass	2.52
1992	Chisel	Alfalfa	1.64
		Native Mix	1.53
		Precrop Mix	2.09
		Pub. Wheatgrass	2.38
		Tall Wheatgrass	2.38
	Subsoil	Alfalfa	1.31
		Native Mix	1.52
		Precrop Mix	1.72
		Pub. Wheatgrass	2.12
		Tall Wheatgrass	2.29

Table A29. Mean forage yields from the Knife River tillage location.

Year	Tillage	Crop	Yield
			(Mg ha^{-1})
1990	Chisel	Alfalfa	1.30
		Native Mix	2.39
		Precrop Mix	2.72
		Pubescent Wheatgrass	3.39
		Tall Wheatgrass	3.86
	Subsoil	Alfalfa	2.26
		Native Mix	3.20
		Precrop Mix	3.19
		Pubescent Wheatgrass	4.10
		Tall Wheatgrass	3.60
1991	Chisel	Alfalfa	2.24
		Native Mix	3.02
		Precrop Mix	2.47
		Pubescent Wheatgrass	4.20
		Tall Wheatgrass	3.42
	Subsoil	Alfalfa	2.11
		Native Mix	3.31
		Precrop Mix	3.63
		Pubescent Wheatgrass	4.44
		Tall Wheatgrass	3.33
1992	Chisel	Alfalfa	1.64
		Native Mix	1.70
		Precrop Mix	2.89
		Pubescent Wheatgrass	2.89
	Subsoil	Alfalfa	1.76
		Native Mix	2.32
		Precrop Mix	2.70
		Pubescent Wheatgrass	3.20
		Tall Wheatgrass	2.02

Table A30. Selected mean root length densities obtained from the Glenharold location.

Year	Tillage	Crop	Depth (m) 0-0.15	0.3-0.45	0.6-0.75	0.9-1.05	1.20-1.35
					(km m^{-3})		
1989	Chisel	Alfalfa	7.9	4.5	0	0	0
		Native Mix	22.8	5.4	0	0	0
		Precrop Mix	12.9	2.9	0	0	0
		Pub. Wheatgrass	23.1	5.6	0	0	0
		Small Grain	34.0	7.4	0	0	0
		Tall Wheatgrass	13.7	6.5	0	0	0
	Subsoil	Alfalfa	12.0	5.5	0	0	0
		Native Mix	12.7	2.4	0	0	0
		Precrop Mix	26.1	11.9	0	0	0
		Pub. Wheatgrass	15.1	2.7	0	0	0
		Small Grain	38.8	13.9	0	0	0
		Tall Wheatgrass	15.6	3.3	0	0	0
1990	Chisel	Alfalfa	38.2	4.1	5.3	3.7	0
		Native Mix	55.1	11.2	0.6	0	0
		Precrop Mix	78.9	24.3	6.8	3.1	0
		Pub. Wheatgrass	67.2	12.6	2.7	0	0
		Small Grain	28.3	1.3	0	0	0
		Tall Wheatgrass	56.4	7.3	2.7	0	0
	Subsoil	Alfalfa	28.5	5.3	3.6	2.5	0
		Native Mix	72.1	24.6	7.5	0	0
		Precrop Mix	62.8	15.6	10.9	0	0
		Pub. Wheatgrass	76.1	23.7	3.4	1.0	0
		Small Grain	40.0	2.0	0	0	0
		Tall Wheatgrass	69.6	18.6	2.3	0	0
1991	Chisel	Alfalfa	57.2	15.0	4.3	2.8	2.2
		Native Mix	57.9	8.6	0.1	0	0
		Precrop Mix	48.6	17.6	1.9	0.7	0
		Pub. Wheatgrass	32.1	6.5	0.3	0	0
		Small Grain	29.8	8.4	0.3	0	0
		Tall Wheatgrass	34.4	5.7	0.1	0	0
	Subsoil	Alfalfa	28.8	13.7	6.0	12.1	3.3
		Native mix	42.6	12.9	4.9	1.4	0
		Precrop Mix	29.9	27.5	2.0	0	0
		Pub. Wheatgrass	36.5	13.6	4.2	0.5	0
		Small Grain	30.7	10.0	0.7	0	0
		Tall Wheatgrass	51.1	17.0	2.9	0	0
1992	Chisel	Alfalfa	105.3	25.2	10.6	6.9	0
		Native Mix	130.8	41.0	9.9	0	0
		Precrop Mix	152.7	14.5	9.7	0	0
		Pub. Wheatgrass	95.3	13.2	9.1	0	0
		Small Grain	32.6	7.1	0.3	0	0
		Tall Wheatgrass	82.9	32.2	12.0	0	0

Table 30 continued.

Year	Tillage	Crop	0-0.15	0.3-0.45	0.6-0.75	0.9-1.05	1.2-1.35
	Subsoil	Alfalfa	85.4	9.4	7.1	0	0
		Native Mix	88.9	28.8	3.8	0	0
		Precrop Mix	142.0	51.8	0.7	0	0
		Pub. Wheatgrass	108.3	72.6	6.6	0	0
		Small Grain	25.5	4.9	0	0	0
		Tall Wheatgrass	73.6	8.9	0	0	0

Table A31. Selected mean root mass densities obtained from the Glenharold location.

Year	Tillage	Crop	Depth (m)				
			0-0.15	0.3-0.45	0.6-0.75	0.9-1.05	1.20-1.35
					($kg\ m^{-3}$)		
1989	Chisel	Alfalfa	0.72	0.05	0	0	0
		Native Mix	0.16	0.05	0	0	0
		Precrop Mix	0.14	0.01	0	0	0
		Pub. Wheatgrass	0.24	0.03	0	0	0
		Small Grain	0.33	0.07	0	0	0
		Tall Wheatgrass	0.16	0.04	0	0	0
	Subsoil	Alfalfa	1.39	0.23	0	0	0
		Native Mix	0.09	0.01	0	0	0
		Precrop Mix	0.20	0.08	0	0	0
		Pub. Wheatgrass	0.11	0.02	0	0	0
		Small Grain	0.36	0.12	0	0	0
		Tall Wheatgrass	0.21	0.02	0	0	0
1990	Chisel	Alfalfa	3.66	0.39	0.08	0.03	0
		Native Mix	0.98	0.11	0.01	0	0
		Precrop Mix	0.87	0.25	0.07	0.02	0
		Pub. Wheatgrass	0.88	0.09	0.02	0	0
		Small Grain	0.23	0.03	0	0	0
		Tall Wheatgrass	1.16	0.08	0.04	0	0
	Subsoil	Alfalfa	3.06	0.20	0.06	0.02	0
		Native Mix	1.72	0.22	0.03	0	0
		Precrop Mix	0.77	0.10	0.07	0	0
		Pub. Wheatgrass	1.10	0.23	0.06	0.01	0
		Small Grain	0.24	0.10	0	0	0
		Tall Wheatgrass	1.44	0.15	0.02	0	0
1991	Chisel	Alfalfa	10.52	0.51	0.18	0.04	0.04
		Native Mix	1.77	0.19	<0.01	0	0
		Precrop Mix	1.44	0.31	0.03	0.01	0
		Pub. Wheatgrass	0.87	0.11	<0.01	0	0
		Small Grain	0.23	0.07	<0.01	0	0
		Tall Wheatgrass	1.07	0.12	<0.01	0	0
	Subsoil	Alfalfa	4.02	2.18	0.32	0.23	0.03
		Native mix	1.14	0.24	0.07	0.01	0
		Precrop Mix	0.91	0.05	0.02	0	0
		Pub. Wheatgrass	1.63	0.21	0.08	0.01	0
		Small Grain	0.28	0.10	<0.01	0	0
		Tall Wheatgrass	1.44	0.28	0.05	0	0

Table A31 continued.

Year	Tillage	Crop	0-0.15	0.3-0.45	0.6-0.75	0.9-1.05	1.2-1.35
1992	Chisel	Alfalfa	10.82	0.90	0.11	0.06	0
		Native Mix	4.57	0.53	0.10	0	0
		Precrop Mix	3.78	0.17	0.12	0	0
		Pub. Wheatgrass	3.27	0.11	0.07	0	0
		Small Grain	0.22	0.05	<0.01	0	0
		Tall Wheatgrass	1.65	0.42	0.15	0	0
	Subsoil	Alfalfa	4.36	0.08	0.06	0	0
		Native Mix	1.51	0.25	0.05	0	0
		Precrop Mix	3.80	0.55	0.01	0	0
		Pub. Wheatgrass	1.66	1.01	0.05	0	0
		Small Grain	0.15	0.03	0	0	0
		Tall Wheatgrass	1.55	0.09	0	0	0

Table A32. Selected mean root length densities obtained from the Knife River location.							
			Depth (m)				
Year	Tillage	Crop	0-0.15	0.3-0.45	0.6-0.75	0.9-1.05	1.20-1.35
			(km m^{-3})				
1989	Chisel	Alfalfa	8.6	3.1	0	0	0
		Native Mix	7.5	1.8	0	0	0
		Precrop Mix	12.9	3.0	0	0	0
		Pub. Wheatgrass	13.1	1.7	0	0	0
		Small Grain	37.8	6.0	1.1	0	0
		Tall Wheatgrass	16.0	0.5	0	0	0
	Subsoil	Alfalfa	4.4	1.7	0	0	0
		Native Mix	18.8	2.5	0	0	0
		Precrop Mix	15.6	4.9	0	0	0
		Pub. Wheatgrass	12.9	1.1	0	0	0
		Small Grain	43.3	5.6	1.1	0	0
		Tall Wheatgrass	24.7	2.1	0	0	0
1990	Chisel	Alfalfa	20.5	9.6	6.4	6.9	0
		Native Mix	64.2	0.7	1.1	0	0
		Precrop Mix	47.6	13.6	7.5	0.7	0
		Pub. Wheatgrass	51.1	3.6	2.1	0	0
		Small Grain	16.3	21.9	0	0	0
		Tall Wheatgrass	35.0	0.4	1.5	0.2	0
	Subsoil	Alfalfa	27.9	9.9	5.4	1.6	0
		Native Mix	32.8	3.8	0.6	1.2	0
		Precrop Mix	27.7	5.7	6.0	1.2	0
		Pub. Wheatgrass	52.7	6.9	1.2	0.6	0
		Small Grain	19.3	6.9	6.5	0	0
		Tall Wheatgrass	40.7	2.5	0.6	0	0
1991	Chisel	Alfalfa	28.3	10.4	1.4	3.5	1.2
		Native Mix	43.4	9.1	1.7	0.5	0.4
		Precrop mix	39.4	3.9	4.4	0.4	0
		Pub. Wheatgrass	49.3	2.9	3.1	0.3	0
		Small Grain	24.1	4.8	0	0	0
		Tall Wheatgrass	48.8	4.5	2.9	0.8	0
	Subsoil	Alfalfa	32.9	10.7	8.8	9.6	1.4
		Native Mix	49.8	18.9	1.9	0.6	0
		Precrop Mix	34.2	5.8	2.1	4.2	0
		Pub. Wheatgrass	41.9	8.0	3.4	0.3	0
		Small Grain	25.0	6.5	0.5	0	0
		Tall Wheatgrass	43.9	14.2	3.6	2.5	0

Table A32 continued.

Year	Tillage	Crop	0-0.15	0.3-0.45	0.6-0.75	0.9-1.05	1.2-1.35
1992	Chisel	Alfalfa	68.9	41.0	8.9	5.0	5.0
		Native Mix	134.9	4.1	14.8	3.7	43.0
		Precrop mix	105.8	14.0	15.4	14.0	8.0
		Pub. Wheatgrass	80.1	5.2	11.0	0.6	0.5
		Small Grain	25.6	11.5	0	0	0
		Tall Wheatgrass	71.3	6.1	1.7	1.1	0
	Subsoil	Alfalfa	91.3	13.5	15.7	4.5	5.9
		Native Mix	102.3	37.6	6.9	2.7	1.8
		Precrop Mix	76.3	18.0	8.4	2.1	0
		Pub. Wheatgrass	155.3	13.3	6.1	2.9	1.3
		Small Grain	20.4	22.3	0	0	0
		Tall Wheatgrass	90.7	41.7	5.1	0	0

Table A33. Selected mean root mass densities obtained from the Knife River location.

Year	Tillage	Crop	Depth (m) 0-0.15	0.3-0.45	0.6-0.75	0.9-1.05	1.2-1.35
					($kg\ m^3$)		
1989	Chisel	Alfalfa	0.56	0.02	0	0	0
		Native Mix	0.09	0.01	0	0	0
		Precrop Mix	0.13	0.18	0	0	0
		Pub. Wheatgrass	0.15	0.02	0	0	0
		Small Grain	0.31	0.05	0.01	0	0
		Tall Wheatgrass	0.20	0.01	0	0	0
	Subsoil	Alfalfa	0.51	0.03	0	0	0
		Native Mix	0.14	0.01	0	0	0
		Precrop mix	0.15	0.05	0	0	0
		Pub. Wheatgrass	0.22	0.01	0	0	0
		Small Grain	0.31	0.04	0.04	0	0
		Tall Wheatgrass	0.29	0.02	0	0	0
1990	Chisel	Alfalfa	8.55	0.37	0.09	0.09	0
		Native Mix	1.01	0.01	<0.01	0	0
		Precrop mix	0.75	0.22	0.09	0.01	0
		Pub. Wheatgrass	1.46	0.06	0.02	0	0
		Small Grain	0.10	0.09	<0.01	0	0
		Tall Wheatgrass	1.23	0.01	0.01	<0.01	
	Subsoil	Alfalfa	5.81	0.58	0.06	0.01	0
		Native Mix	1.30	0.05	0.01	0.01	0
		Precrop Mix	0.85	0.10	0.11	0.01	0
		Pub. Wheatgrass	0.97	0.14	0.02	0.01	0
		Small Grain	0.11	0.04	0.03	0	0
		Tall Wheatgrass	1.64	0.04	0.01	0	0
1991	Chose;	Alfalfa	4.78	0.46	0.02	0.11	0.01
		Native Mix	1.10	0.21	0.03	<0.01	<0.01
		Precrop Mix	0.89	0.05	0.05	<0.01	0
		Pub. Wheatgrass	1.97	0.08	0.05	<0.01	0
		Small Grain	0.23	0.04	0	0	0
		Tall Wheatgrass	1.87	0.48	0.04	0.03	0

Table A33 continued.

Year	Tillage	Crop	Depth (m)				
			0-0.15	0.3-0.45	0.6-0.75	0.9-1.05	1.2-1.35
	Subsoil	Alfalfa	4.01	1.02	0.26	0.14	0.01
		Native Mix	1.47	0.41	0.04	0.01	0
		Precrop Mix	1.50	0.15	0.03	0.05	0
		Pub. Wheatgrass	1.51	0.21	0.05	<0.01	0
		Small Grain	0.23	0.04	0.01	0	0
		Tall Wheatgrass	2.22	0.36	0.04	0.04	0
1992	Chisel	Alfalfa	11.45	0.91	0.10	0.73	0.05
		Native Mix	1.94	0.04	0.12	0.09	0.07
		Precrop mix	1.67	0.06	0.13	0.17	0.08
		Pub. Wheatgrass	2.14	0.05	0.11	0.01	<0.01
		Small Grain	0.18	0.06	0	0	0
		Tall Wheatgrass	1.38	0.16	0.01	0.01	0
	Subsoil	Alfalfa	1.31	0.31	0.27	0.04	0.02
		Native Mix	1.78	0.52	0.09	0.02	0.01
		Precrop mix	1.55	0.45	0.11	0.01	0
		Pub. Wheatgrass	3.18	0.05	0.11	0.03	<0.01
		Small Grain	0.18	0.16	0	0	0
		Tall Wheatgrass	3.03	0.53	0.05	0	0

Table A34. Mean soil bulk densities obtained from the Falkirk trench location.

Year	Topsoil Depth	Subsoil+	Depth (m) 0-0.3	0.3-0.6	0.6-0.9	0.9-1.2
	(m)		(Mg m^{-3})			
1979	0.23	SL	1.77	1.85	1.42	1.07
		SL+C	1.43	1.43	1.31	1.33
		CL	1.07	1.22	1.13	1.29
		SiCL	1.24	1.45	1.45	1.51
	0.46	SL	1.34	1.56	1.40	1.48
		SL+C	1.41	1.57	1.66	1.57
		CL	1.21	1.58	1.50	1.46
		SiCL	1.31	1.38	1.45	1.50
	0.69	SL	1.63	1.66	1.56	1.18
		SL+C	1.62	1.77	1.58	1.70
		CL	1.16	1.34	1.30	1.36
		SiCL	1.26	1.48	1.48	1.42
1990	0.23	SL	1.66	1.78	2.13	1.82
		SL+C	1.34	1.58	1.81	1.77
		CL	1.35	1.49	1.57	1.66
		SiCL	1.38	1.57	1.59	1.58
	0.46	SL	1.22	2.12	2.12	2.27
		SL+C	1.29	1.56	1.59	1.47
		CL	1.33	1.51	1.70	1.46
		SiCL	1.33	1.51	1.62	1.53
	0.69	SL	1.35	1.51	1.95	2.04
		SL+C	1.29	1.48	1.55	1.58
		CL	1.41	1.51	1.63	1.53
		SiCL	1.29	1.50	1.54	1.57

+SL = sandy loam, SL+C = sandy loam plus clay, CL = clay loam, SiCL = silty clay loam.

Table A35. Mean soil bulk densities in 1986 and 1992 from the Center topography location.

Year	Position	Depth (m) 0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5
				(Mg m^{-3})		
				Forage Area		
1986	Summit	1.40	1.55	1.49	1.57	1.56
	Shoulder	1.26	1.60	1.60	1.47	1.42
	Backslope	1.25	1.54	1.63	1.57	1.59
	Footslope	1.36	1.56	1.54	1.46	1.57
1992	Summit	1.39	1.75	1.70	1.80	1.70
	Shoulder	1.37	1.78	1.84	1.72	1.68
	Backslope	1.34	1.78	1.85	1.76	1.78
	Footslope	1.22	1.63	1.70	1.78	1.84
				Small Grain Area		
1986	Summit	1.34	1.68	1.66	1.64	1.62
	Shoulder	1.16	1.55	1.56	1.56	1.52
	Backslope	1.26	1.62	1.66	1.54	1.51
	Footslope	1.12	1.52	1.54	1.52	1.52
1992	Summit	1.35	1.86	1.76	1.77	1.78
	Shoulder	1.51	1.86	1.76	1.70	1.63
	Backslope	1.30	1.82	1.88	1.97	1.74
	Footslope	1.35	1.63	1.73	1.69	1.75

Table A36. Mean soil bulk densities in 1986 and 1992 from the Falkirk topography location.

		Depth (m)				
Year	**Position**	**0-0.3**	**0.3-0.6**	**0.6-0.9**	**0.9-1.2**	**1.2-1.5**
				($Mg\ m^{-3}$)		
				Forage Area		
1986	Summit	1.30	1.52	1.56	1.69	1.60
	Shoulder	1.35	1.45	1.48	1.46	1.54
	Backslope	1.36	1.39	1.38	1.48	1.51
	Footslope	1.31	1.48	1.61	1.60	1.36
1992	Summit	1.31	1.70	1.83	1.74	1.72
	Shoulder	1.16	1.61	1.66	1.71	1.73
	Backslope	1.20	1.45	1.47	1.52	1.52
	Footslope	1.35	1.68	1.79	1.74	1.64
				Small Grain Area		
1986	Summit	1.33	1.51	1.62	1.60	1.54
	Shoulder	1.26	1.25	1.39	1.60	1.53
	Backslope-Top	1.20	1.46	1.40	1.56	1.58
	-Middle	1.06	1.44	1.44	1.44	1.55
	-Bottom	1.31	1.39	1.38	1.42	1.54
	Footslope	1.28	1.38	1.46	1.51	1.58
	Toeslope	1.13	1.46	1.56	1.59	1.56
1992	Summit	1.29	1.75	1.72	1.80	1.77
	Shoulder	1.40	1.48	1.61	1.78	1.77
	Backslope-Top	1.29	1.54	1.62	1.73	1.79
	-Middle	1.29	1.55	1.55	1.73	1.84
	-Bottom	1.25	1.38	1.45	1.44	1.71
	Footslope	1.31	1.59	1.54	1.74	1.82
	Toeslope	1.23	1.52	1.76	1.82	1.82

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