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. Soil Strength

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.