EFFECTS OF ANIMAL TRAFFIC ON SOIL COMPACTION IN WHEAT PASTURES IN OKLAHOMA

By

CHAW FOH CHEE

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Thesis Approved:

Eugene G. Krenzer, Jr.
Thesis Adviser

John F. Stone

Ronald W. McNew

Norman N. Durham
Dean of the Graduate Collage

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CHAPTER I

INTRODUCTION

Small grains have been a valuable source of high quality forage for grazing livestock in Oklahoma for a long time (Staten and Heller, 1949). In the Southern Great Plains, especially in Oklahoma, Kansas, and Texas, hard red winter wheat (Triticum aestivum L.) has been a source of high quality forage and also a timely feed source. Farmers in this region typically utilize hard red winter wheat for grazing during its vegetative growth stage in fall, winter, and early spring. In the spring, before the jointing stage, livestock are removed to allow reproductive development for grain production.

According to Oklahoma Agricultural Statistics (1985), winter wheat is by far the most important crop in Oklahoma. It occupies about 8 million acres of the total farmland. Every year 50 to 90 percent of the wheat fields are grazed by about 1.5 million head of stocker cattle.

With increasing numbers of farmers practicing No-Till, Lo-Till, or some form of conservation tillage system, there is concern with the level of soil compaction caused by grazing cattle. Scientific literature reveals that animal traffic will compact soil and also reduce crop yield if compaction exceeds a certain level. Meredith and Patrick (1961) concluded that soil compaction can accumulate over time if no efforts were taken to plow the fields. Therefore, farmers practicing Lo-Till or No-Till or some form of conservation tillage may need to be concerned with the level of soil compaction caused by grazing animals. This is because under No-Till, Lo-Till, or conservation tillage practices, wheat fields are either not plowed or are plowed infrequently and the compaction created by grazing may not be alleviated.

In Oklahoma, grazing usually starts as early as October and lasts through late February or early March. During this period, Oklahoma receives snow and rain. As a result, the soil in the wheat pastures may be soft and plastic and such soil conditions are most vulnerable to compaction.

Very limited information is available concerning the level of soil compaction caused by cattle on wheat pastures in Oklahoma. Quantitative data on the effects of animal traffic on soil strength and soil bulk density are needed. In this study, various soil characteristics were evaluated as a mean of understanding problems associated with soil compaction on wheat pastures in Oklahoma.

The objectives of this study were:

A. To quantify the effect of grazing on soil strength and bulk density in grazed and ungrazed areas in wheat pastures.

B. To determine the depth to which differences in bulk density and soil strength occur in the soil profile as a result of grazing.

CHAPTER II

PREVIOUS WORK AND LITERATURE REVIEW

Extensive research over the past decades has established that the growth, development, and yield of crops are adversely affected by soil compaction (Phillips and Kirkham, 1962; Bilanski and Varma, 1976). These effects resulted from the changes in physical properties of the soil, in particular its moisture content, bulk density, and soil strength.

Lull (1959) defined soil compaction as packing together of soil particles by instantaneous forces exerted at the soil surface resulting in an increase in soil bulk density through a decrease in pore space.

Even though cattle weigh less than a tractor, the pressure generated by the cattle can cause soil compaction. Lull (1959) concluded an average animal weighing 612.9 kg was capable of exerting 164.8 kPa of pressure from one foot when it was not moving. However, when the animal was moving it could exert as much as four times the pressure as when it was stationary. This was because animal often put their entire weight on one foot as they move. This pressure could cause a substantial amount of compaction to soil especially when the soil is wet and plastic.

Several studies have shown the response of soil to grazing in pasture or range situations by the distribution of soil bulk density. Galbraith (1971), in a study conducted in Colorado reported a significant bulk density difference between nongrazed and heavily grazed sites on the Ascalon soil series. The heavily grazed sites showed a 12 percent increase in bulk density over the plots not subjected to animal traffic. According to Van Haveren (1983), bulk density from heavily grazed plots was 6 percent higher than lightly grazed plots. On the fine-textured soils, bulk densities for areas subjected to heavy grazing were significantly greater (13.4 percent) than light grazing and significantly greater (11.8 percent) than moderate grazing. Rauzi and Hanson (1966) in a study conducted in northeastern Colorado found differences between bulk densities of silty clay soils on heavily, moderately, and lightly grazed pastures were all highly significant.

Alderfer and Robinson (1947) found compaction from grazing was limited mostly to the 2.5 cm surface layer. From various pasture sites with clay loam and sandy loam soils in Pennsylvania, they found bulk densities in the surface 2.5 cm layer ranged from 1.54 g cc^{-1} to 1.91 g cc^{-1} for heavily grazed sites and from 1.09 g cc^{-1} to 1.51

g cc^{-1} for ungrazed and lightly grazed sites. Linnartz et al. (1966) indicated that in comparison with no grazing, bulk density of moderate grazed pasture increased 5 percent in the top 10 cm, 2 percent in the 15 cm to 25 cm depth, and 1 percent in the 30 cm to 40 cm depth. As for the heavily grazed pasture, the bulk density increased by 7, 4, and 2 percent for the respective depths. From an experiment conducted in Oklahoma, Rhoades et al. (1964) indicated the soil bulk density for plots that were subjected to heavy grazing had an averaged value of 1.72 g cc^{-1} while the ungrazed exclosures had only 1.56 g cc^{-1} for the 10 cm to 15 cm depth. He also observed an increase in bulk density at 91 cm depth of a loamy fine sand after being lightly grazed for 20 years.

In contrast, Daubenmire and Colwell (1942) and Meeuwig (1965) found no significant differences in bulk density between grazed and ungrazed areas. Laycock and Conrad (1967) found no measurable compaction due to grazing on both sandy loam and clay sites in Utah. They attributed their conflicting results to varying soil types, soil moisture, and other conditions.

Among the soil factors that influence a soil response to compaction are texture, depth of soil profile, organic matter, and moisture content. Van Haveren (1983) found bulk density for fine-textured soil increased with grazing intensity and declared no significant differences in bulk density for coarse-textured soil. Hill and Cruse (1985) reported bulk density increased with depth. Free et al. (1947) showed for Honeoye silt loam that an increase of bulk density from 1.47 g cc^{-1} to 1.61 g cc^{-1} was associated with a decrease in organic matter content of 4.1 to 2.5 percent. They also indicated that reduction in soil moisture also increased the bulk density of the soil. Camp and Gill (1969) reported bulk densities of Lloyd clay, Colo silty clay loam, and Congaree silt increased as the water content decreased. In general, compaction increases soil bulk density, however, other soil factors like texture, moisture content, and organic matter governed how much it changes.

Considerable study has been given to the relationship between soil moisture and compaction in respect to the objective of determining the moisture content that would give the greatest degree of compaction under equal amounts of stress. Chancellor (1976) considered that water content was the most dominant factor influencing the amount of compaction which results from the passage of wheels over agricultural soils. Blackwell (1979), using two field soils (sandy loam and loam) at different water contents and initial bulk densities, measured the change in compaction resulting from passage of a tractor's rear tire. When the soil water content was 23 percent, the increase in bulk density at a depth of 150 mm was four times larger than when the water content was 14 percent. Studies had shown that the greatest compaction can be achieved when the soil was at a moisture content slightly less than the plastic limit (Markwick, 1945). Buchanan (1942) found in dry soils the resistance of the particles to rearrangement was great, for the thin water films provide little lubrication. Also, the effect of surface tension was pronounced so the stress was partially neutralized. The addition of moisture improved lubrication and neutralized the surface tension forces so compaction was easier to achieve. As a result, compactability of soil is ultimately affected by soil moisture content and the right amount of moisture content present will allow soil to be compacted to its maximum.

In addition to influencing compactability of soil, soil moisture content is also an important variable when collecting soil strength data. Bryant et al. (1972) stated that soil strength increased with increasing trampling pressure. Significant difference in soil strength was found between 0 and 60 trips/cow and 60 to 120 trips/cow. According to Willatt (1986), there was significant difference in soil strength values between all treatments (number of tractor passes), that is, zero-pass treatment < one pass treatment < six pass treatment. Voorhees et al. (1978) concluded penetrometer resistance values in the wheel track were significantly higher than in the nontracked area to a depth of 30 cm for five years of study.

Empirical studies on soil resistance to penetrating probes indicate interaction in effects between bulk density and moisture tension on soil strength. Ellis et al. (1977) and Carter and Tavernetti (1968) found a positive correlation between soil bulk density and soil resistance to penetration. Gerard et al.,(1982) asserted that increased in soil moisture content tends to decrease soil strength. Barley et al. (1965), Henry and McKibben (1967), Mazurak and Pohlman (1968), Taylor and Bruce (1968), and Taylor and Gardner (1963) agree that an increase in soil strength of clay-sand mixtures was a result of an increase in matric suction of water resulting in greater cohesive forces between particles. Camp and Gill (1969) suggested that for a non-shrinking soil, the influence of soil moisture content on penetration resistance may be explained by an increase in cohesion and angle of internal friction as the soil dries, which causes an increase in soil strength. Bilanski and Varma (1976) showed a curvilinear effect of moisture tension on soil resistance. They found soil resistance increased to maximum with drying and then decreased with further increase in moisture tension due to the breaking of interparticle moisture bonds. Mirreh and Ketcheson (1972) showed increasing bulk density and decreasing soil matric potential would increase soil strength. The resistance was increased as soil was compacted. They indicated that "...the expression of soil resistance was a function of both bulk density and matric pressure. This interrelation of soil bulk density and matric pressure renders the resistance behavior of soils to be unpredictable unless related to both these parameters simultaneously".

Other soil factors that influence soil strength are depth of soil profile and soil texture. Hill and Cruse (1985) found soil strength increased with depth. Gerard et al. (1982) found bulk density and depth were positively correlated with soil strength. Spivey et al. (1986) and Gupta and Larson (1979) found a positive correlation between percent sand and probe resistance and a negative correlation between percent clay and organic matter with probe resistance. In contrast, Gerard et al. (1982) found that increases in the percent of clay content increases soil strength. Increased soil strength could be the result of other factors that were not necessarily correlated with soil compaction, for example, changes in base saturation, changes in organic matter, or addition in polyelecrolytes. According to literature reviewed, soil strength is directly related to bulk density, moisture content, depth of soil profile, and indirectly related to soil texture. Therefore, soil strength should not be used as the only variable to evaluate soil compaction.

Apart from influencing soil bulk density, soil texture also plays an important role in soil compaction. Lull

(1959) concluded that medium-textured and well-aggregated soil had the potential for the greatest compaction because of the well distributed particles-size. Raney et al. (1955) reported hardpans produced by compaction from vehicles or trampling were most commonly found in medium-textured soils (loams, sandy loams, and silt loams). Rauzi and Hanson (1966) found differences between bulk densities of silty clay soils on heavily, moderately, and lightly grazed pastures were all highly significant. Van Haveren (1983) found coarse-textured soil bulk densities were not affected by grazing intensity and bulk densities on fine-textured soils increased with grazing pressure. Conversely, Anazodo et al. (1983) reported soil compaction on clay soil had less dramatic effects on soil density, soil resistance to root penetration and soil porosity as compared to sandy loam soil. On the overall, medium-textured soil has the greatest potential for compaction.

Numerous experiments have been conducted to evaluate effects of soil compaction on the soil physical properties and the productivity of the sites. One of the obvious adverse effects of compaction is the impedance of root growth. Raghavan et al. (1979) reported root distribution and root growth were significantly affected by soil compaction. Taylor and Gardner (1963) indicated reduction in root penetration was associated with an increase in soil bulk density. Taylor (1971) found root elongation rate was inversely related to soil strength, all other plant growth conditions being non-limiting. Taylor and Gardner (1963) reported there was a highly significant negative linear correlation ($r = -0.96$) between the soil strength and root penetration percentage. Ericksson et al. (1974) reported that root growth of wheat seedlings were progressively reduced when the soil was subjected to surface pressure in excess of 200 kPa and the limiting penetration resistance for root growth was reported to be between 0.8 MPa and 5 MPa. In other research, Taylor et al. (1966) found more than 60 percent of the taproots penetrated when penetrometer resistance was 500 kPa, but only 35 percent penetrated when penetrometer resistance was 999.7 kPa, and ceased entirely at a resistance of 2499.3 kPa. In Australia (Reeves et al.,1984), spring wheat grown in compacted soil had 155 g m^{-2} of roots and in the uncompacted soil 240 g m^{-2} to a depth of 200 mm. The compacted layer was rammed and had an average bulk density of 1.52 Mg m^{-3} in the 0 to 200 mm depth, while in the uncompacted soil it was 1.32 Mg m^{-3}. As a whole, soil compaction impedes root penetration and in turn reduces root growth.

Not only does compaction affect root penetration, but also top growth of plants. Carmi and Heuer (1981) reported that restriction of root growth in bean plants growing in very small pots led to the development of dwarf plants.

Root systems or entire plants of crops growing in compacted soil may be stunted (Pumphery et al., 1980; Russel and Goss, 1974). Voorhees (1977) concluded that even if the total amount and depth of root growth was not altered by compaction, the "geometry" of the root system could be altered.

Another soil property that is affected by compaction is porosity. Soil cores from ungrazed areas contained greater total pore space than those from grazed paddocks at 0 to 10 cm and 15 cm to 25 cm. In the upper 10 cm, pore spaces averaged 43.4 percent on heavily grazed range, as compared to 47.0 percent on the ungrazed . In the 15 cm to 25 cm layer, it was 40.4 percent under grazing and 42.5 percent on protected range (Linnartz et al., 1966). In southern Wisconsin, Steinbrenner (1951) found the total porosity was greater in ungrazed than grazed woodlands. For six paired areas, total pore spaces ranged from 64.5 to 72.5 percent in ungrazed areas as compared with 57.5 to 67.0 percent for grazed soils. Associated ranges of macroscopic pore spaces were 16.5 to 37.0 percent and 12.5 to 18.0 percent respectively. Therefore, in general, total porosity decreases with increasing level of soil compaction.

Several authors (Barber, 1962; Labanauskas et al., 1975; Bolton et al., 1979; Weirsum, 1979; Ide et al., 1982) found a decrease in the concentration of the nutritive elements in the crop where a reduction of the rooting zone was caused by compaction.

The ultimate adverse effect of soil compaction is the reduction of yield or the reduction in the productivity of the compacted sites. Nagpal et al., (1967) reported as the bulk density of soil increased from 1.27 to 1.67 g ml^{-1}, the yield of dry matter of wheat decreased from 4.50 to 2.94 grams. Canarche et al. (1984) indicated yield of maize followed a negative linear trend with increasing bulk density and there was an overall decrease in yield of 13 kg ha^{-1} for each 1 kg m^{-3} increased in bulk density. Yield from the alfalfa-brome-Ladino pasture on the Ontonogan clay loam showed the effect of animal traffic. One season of pasturing reduced yield by 20 percent (Tanner and Mamaril, 1959). Eriksson et al. (1974) estimated that cereal yields on clay soil in Sweden would be increased by about 6 percent in the absence of compaction from wheel traffic. Therefore, it is obvious to conclude soil compaction impedes the development of plant parts above and below the soil surface. And the ultimate result from soil compaction is yield reduction.

Literature reviewed indicates much research utilizes soil bulk density as the only tool to determine level of soil compaction. Yet, according to Laycock and Conrad (1967) bulk density should not be used to compare the effects of grazing on soil compaction unless soil moisture conditions were approximately the same in the areas compared. This is because bulk density varies with amount of soil moisture. Other research workers used only soil strength parameter as a means to measure level soil compaction. However, soil strength alone is also inadequate to give an accurate result. According to Mirreh and Ketcheson (1972) soil strength was a function of soil bulk density and matric potential because these two parameters rendered the resistance behavior of soil. Therefore in this experiment soil strength, soil moisture, and soil bulk density are the soil characteristics used to quantify the effect of animal traffic and determine how deep in the soil profile compaction occurs.

CHAPTER III

MATERIALS AND METHODS

The study was conducted on three fields at different locations during the 1986-1987 wheat growing season. Field one had Taloka fine, mixed, thermic Mollic Albaqualfs (silt loam 1-2 percent slope) and was located at the Eastern Research Station in Haskell, Oklahoma. Field two was located at Agronomy Station in Perkins, Oklahoma, with Teller fine loamy, mixed, thermic udic Argiustolls (fine sandy loam 1-3 percent slope). The third field was located on a farmer's field near near Lahoma, Oklahoma, which had Pond Creek fine-silty, mixed, thermic Udic Argiustolls (silt loam 0.5 percent slope) as soil type.

In all three locations, soil strength readings, soil bulk density, and soil moisture content data were collected in two specific sampling date. The first sampling date was before cattle were placed into the wheat fields, but after the wheat emerged. The second sampling date was immediately after cattle were removed from the wheat pastures.

The experiment in Haskell started off with seven head mature beef cows on a five acre field in November, 1986.

By December 3, three animals were removed and were replaced on February 18, 1987. The cattle grazed the wheat pasture for about 147 days and there were 1.4 head of cattle per acre or 205 animal days per acre of wheat pasture (Table I). The previous crop was oats planted in early fall of 1985. After oat had been harvested and before wheat was planted for 1986-1987 season, the field was disked several times.

In Perkins, the experiment was conducted on an 11.5 acre field with 30 cows. All 30 head of animals were removed two weeks after they were placed into the field. Three weeks later, the animals were placed back on the field again. There were about 2.61 head of cattle to an acre of wheat pasture. They grazed for 55 days resulting in 143 animal days per acre (Table I). After 1985-1986 wheat was harvested, this field was tilled by moldboard plowed, offset disked, tandem disked, and springtooth harrowed before wheat was planted for the 1986-1987 season. This field was not subjected to grazing in the past recent years.

In Lahoma, 180 head of cattle weighing at about 420 pounds was placed in the 290 acre field in late November, 1986. On April 23, 1987, the cattle were removed from the field and the average weight of the cattle was approximately 700 pounds. This wheat pasture was grazed for about 75 days and there were approximately 0.62 head of cattle to an acre of wheat pasture. The animal days per acre value was 45 only (Table I). This field had wheat the previous year and was disked, chiseled, swept, springtoothed, and disked again before the wheat was planted.

The first sampling date for Haskell, Perkins, and Lahoma were October 29, 1986, January 8, 1987, and November 26, 1986 respectively. Data for the second sampling date for Haskell and Perkins were collected on March 26, 1987 while data for Lahoma was collected on March 21, 1987. (Table I).

A randomized complete block design with a split plot arrangement and five replications in each location was used in this study. The main plot effect consisted of two treatments, areas subjected to animal traffic and areas not subjected to animal traffic. The subplot treatment was the sampling depth in which cone index values and soil samples were collected.

Grazed and ungrazed areas were separated by exclosures. Each exclosure was covered with a metal structure that looked like a cage with an open base. It consisted of four sides plus a top that were tied together by metal wire upon arrival to the location. These structure had a base measurement of 230 cm in length and 90 cm in width. Five exclosures or replications were randomly placed at each site. After penetrometer readings and soil samples for bulk density and gravimetric water content were taken for the first sampling date, the structures were put in place. The ultimate purpose of the structures was to maintain an area that was not subjected to animal traffic in the field where uncompacted soil readings could be taken after the cattle were removed.

For each sampling date, 12 sets of penetrometer readings were collected from each replication, six sets of readings from the exclosure and the other six sets were collected outside the exclosure (Figure 1). A set of penetrometer readings consisted of values taken from top 42 cm of the soil profile at 2 cm intervals. In the exclosure, three penetrometer reading sites were located on the north side and the other three sites on the south side. The sites in the center divide the exclosure into half. The other two sites were located 71 cm to the right and left of the center sites.

Since cattle had been observed wondering near or along fences or anything that are alien to them, data from area that was subjected to animal traffic was collected 305 cm away from the exclosure. The 305 cm distance was an attempt to avoid locating sampling sites on animal walk paths. For these six sampling sites, two sites were located on the north, east, and west sides of the exclosure. Sampling sites located on the same side were separated by 71 cm. The six sites for the second sampling date were located in the middle of the exclosure. These sites were 15 cm apart. As for the grazed areas, these sites were located 30 cm from the first sampling sites. All penetrometer readings sites in the exclosures were located 15 cm into the exclosures. This distance was to ensure trampling by the cattle along the side of the cage-like structure would not affect penetrometer readings inside the exclosures. In addition, extra caution was taken to make sure subsequent sampling sites were not compacted by the tractor when collecting the first sets of data.

A computerized, tractor-mounted cone penetrometer (Riethmuller et al. 1983 and ASAE S313.1, 1983) was utilized in this experiment to determine the soil strength. The force required to press the 30° circular cone through the soil, expressed in kilo-pascals (kPa), is an index of soil strength called the "cone index". Soil cone index was used exclusively to quantify soil strength throughout this study. The cone penetrometer was calibrated to push the cone into the ground at a uniform rate of 182.9 centimeters per minute. The surface reading was measured at the instant the base of the cone was flushed with the soil surface. Subsequent readings were taken at 2 cm increments. Readings were recorded by the Rockwell AIM 65 computer and a hardcopy of the data was printed on paper tape. The hydraulically operated penetrometer was mounted on the back of a tractor.

For each sampling date, a total of six sets of soil samples for bulk density and gravimetric water content were collected from each replication. Three sets were collected within the exclosure. One set was obtained from the right side of the center cone penetrometer sampling site on the north side of the exclosure and the second from the left side of the center sampling site from the same side. The third set was collected near the center penetrometer sampling site on the south side of the exclosure. Outside the exclosure, one set of soil samples was collected on the north, east and west sides of the exclosure. Sampling sites for first and second sampling date were located 15 cm from the sites where the first and second sampling dates' cone index values were collected. Soil samples were collected to a depth of 42 cm at 3 cm increments.

Soil samples were collected using a special hand driven core sampler from JMC Soil Investigation Equipment. The JMC sampling tube contained a removable rigid acetate liner which had a diameter of 2.3 cm. The liner was cut into 15 pieces, three-centimeter long segments. After the auger had been pulled from the ground, the soil and acetate liner were pushed out from the auger, the soil was cut at the three centimeter precut liner location, and the soil in each segment was then emptied into air-tight cans. Soil samples for each main plot and depth were composited.

The cans were transported to the laboratory and were weighed immediately and dried in 105^{o} C ovens for 48 hours. The weight of dry soil and the empty can weights were determined. Bulk densities were determined as outlined by Black (1965) and expressed as gram per cubic centimeter (g cc^{-1}). The gravimetric water content or mass wetness (w) was determined by dividing the mass of water (M_w) from the soil samples by the mass of solid (M_s) or the dry weight of the soil samples (Hillel, 1982) and expressed in percent.

All soil samples, from each location, collected from the same depth were mixed together. These soil samples were ground and particle size analysis was conducted. Organic matter was oxidized from a 40 gram subsample using 30 percent hydrogen peroxide. The samples were then centrifuged for 30 minutes at 6000 rpm. Following the centrifuging process, the water was drained from the pellet and 50 ml of Calgon solution containing sodium hexametaphosphate was added as a dispersing agent. The samples were placed on a mechanical shaker for 12 hours to enhance the dispersing process. The samples were then transferred to sentimentalizing cylinders and brought to the 1000 ml mark with distilled water. Soil samples in solution were stirred vigorously for one minute with a plunger to ensure all particles were lifted into suspension. Immediately, the hydrometer was slowly lowered into the cylinder. Hydrometer readings were at every 30 seconds for the first 5 minutes, 6 minutes, 7 hours, 8 hours, 9 hours, and 24 hours. Then the soils' textural classes were determined (Black, 1965).

Split plot analyses of variance were performed on the bulk density data, gravimetric water content data, and penetrometer readings for all three locations. If the F values were significant and no compaction by depth interaction existed, the F test was used to determine significance differences between level of compaction and the Least Significant Difference Test (Steel and Torrie, 1960) was used to determine whether significant differences existed between depths. A probability level of 0.05 was used to test significance.

CHAPTER IV

RESULTS AND DISCUSSION

Textural analyses were conducted on soil samples collected from fields in Haskell, Perkins, and Lahoma. For Haskell, the top 39 cm of the soil profile had silt loam texture. Clay loam was found between 39 cm to 42 cm (Table II). Perkins had sandy loam for the top 42 cm of the soil profile (Table III). Silt loam was the soil texture for the surface 21 cm, 24 cm to 33 cm, and 36 cm to 39 cm of the soil profile in Lahoma. Silty clay loam was found between 21 cm and 24 cm and between 39 cm and 42 cm, loam predominated between 33 cm and 36 cm (Table IV).

The cone index values collected across an exclosure in the field at Lahoma are plotted in Figures 2, 3, 4, and 5. Each curve on the graph depicts a depth at which cone index data was collected with 0 on the X-axis being the center of the exclosure. Grazing cattle had no effect on cone index values within 30 cm of the center of the exclosure. The compaction effect increased gradually from 30 cm outward. Therefore, the effect of grazing on cone index values occurred outside the area where measurements were taken after grazing.

The effect of animal traffic on soil strength was determined by the cone index values taken, to 42 cm depth, in grazed and ungrazed areas of the fields. From the split plot analysis of variance performed on soil strength collected prior to grazing or from the first sampling date, there was no evidence of significant (P = 0.05) difference in cone index values between areas to be grazed and those not grazed at Haskell, Perkins, or Lahoma (Figures 6, 7, and 8). Similar statistical analyses were performed on bulk density and gravimetric water content data. There were no significant differences (P = 0.05) in bulk density (Figures 9, 10, and 11) or gravimetric water content (Figures 12, 13, and 14) between the ungrazed exclosures and areas to be subjected to grazing at any of the three locations.

Data collected from the second sampling date revealed that gravimetric water content was affected by grazing treatments. Less soil moisture content was found in the top 9 cm and 15 cm of grazed areas as compared to ungrazed in Haskell and Lahoma respectively (Figures 15 and 16). At Haskell there was a continuous trend in difference, though not significant difference (P = 0.05), in moisture content between the grazed and the ungrazed extending down to 27 cm in the soil profile (Table V). As for the location at Lahoma, the continuous trend of difference in moisture content extended down to 21 cm depth (Table VI). No statistical significant difference (P = 0.05) in gravimetric water content was found in the experiment at Perkins (Table VII). Though no statistical significant difference (P = 0.05) was computed between the two treatment (Figure 17) grazed areas tended to have a higher moisture content than ungrazed areas and the continuing trend of differences extended down to 42 cm of the soil profile.

Grazing significantly (P = 0.05) increased bulk density at all three locations, however, the depth to which differences existed varied with each location. The depth to which significant difference (P = 0.05) was declared in bulk density between grazed and ungrazed areas in Haskell was 9 cm (Table VIII and Figure 18). No trend of difference was observed between the two grazing treatments from 12 cm to 36 cm depth. From 39 to 42 cm, grazed areas' bulk density was significantly higher than ungrazed areas. However, there was no reasons to associate these changes to animal traffic. Figure 19, showed that there was significant difference in bulk density between the two treatments in the top 21 cm of the soil profile at Perkins. Even though not statistically different (P = 0.05), the continuing differences in bulk density between the two treatments extended from 21 cm to 30 cm depth as seen in Table IX. At Lahoma (Figure 20), significant difference in bulk density between the grazed and ungrazed treatments occurred in the top 12 cm in the soil profile and the trend continued down to 21 cm depth (Table X) even though the latter differences were not significantly different.

The average bulk density of soil, from the top 3 cm, from the ungrazed areas in Haskell, Perkins, and Lahoma were 1.362 g cc^{-1}, 1.503 g cc^{-1}, and 1.349 g cc^{-1} while the grazed areas had 1.574 g cc^{-1}, 1.749 g cc^{-1}, and 1.553 g cc^{-1} respectively. The bulk density of the surface soils increased by 15.6 percent, 16.4 percent, and 15.1 percent respectively due to grazing. As for the top 6 cm, increase in bulk density averaged 14 percent in Haskell, 14.6 percent in Perkins, and 12.7 percent in Lahoma. With relation to soil type, Perkins with sandy loam soil type showed a higher percent change in bulk density as well as greater depth of compaction than the two other fields, Haskell and Lahoma, which have silt loam. The higher percent change in bulk density at Haskell than Lahoma may be due to the higher animal days per acre (Table I).

Soil strength as measured by soil cone index values increased as a result of animal traffic. Results from statistical analyses performed on cone index values showed grazing activities significantly ($P = 0.05$) affected cone index values at Haskell, Perkins, and Lahoma. Significant difference ($P = 0.05$) in cone index values in Haskell was limited to the top 16 cm of the profile (Table XI). The grazed area continued to have higher cone index values, though not statistically different, from 16 to 24 cm depth. In contrast, however, between depth 28 cm and 42 cm ungrazed areas had a higher cone index values (Figure 21). Mirreh and Ketcheson (1972) indicated that soil strength was a function of soil bulk density and moisture content. Soil strength and moisture content are inversely related. For the relationship with bulk density, soil strength tends to increase with increasing bulk density. Therefore, the increased cone index values in the top 9 cm was a result of an increased in bulk density and reduction in moisture content. From 9 cm to 24 cm depth, higher cone index values in grazed areas can be attributed to lower moisture content in grazed areas since no difference in bulk density occurred at these depths. On the other hand, higher moisture content was found in grazed areas between 30 cm to 42 cm. This reduces the cone index values in grazed areas between these two depths.

In Table XII significant difference in cone index values between the two treatments at Perkins occurred in the top 30 cm of the soil profile. Differences in cone index values continued to 36 cm in the profile (Figure 22) and these differences was not declared statistically significant (P = 0.05). From the Least Significant Difference test conducted on moisture content from soil samples collected during the second sampling date, no significant difference was found between the two treatments. However, Figure 16 showed that grazed areas had more moisture content than ungrazed areas. Therefore, in the case at Perkins the moisture content actually reduced the cone index values in grazed versus ungrazed areas. Therefore, the increase in cone index values in the top 21 cm of soil resulted from increased bulk density. In addition, cause of the increase in cone index values from 21 to 30 cm can also be attributed to the tendency for bulk density differences. This was because there was a continuous trend of higher bulk density in grazed areas between these two depth.

In Lahoma, depth to which differences in cone index values occurred between grazed and ungrazed areas was in the surface 30 cm in the soil profile (Table XIII and Figure 23). The increase in cone index values in the top 12 cm was attributed to higher soil bulk density and lower moisture content. Since there were continuing differences in soil bulk density and moisture content which were not declared significant, extending from 12 cm to 21 cm depth, the effects of the two factors combine may have resulted in the increase in the cone index values between these two depths.

In contrast to soil bulk density, the maximum change in cone index values was not confined to soil surface. For Haskell (Table XI), the cone index value between 2 cm and 4 cm changed the most, by 2178 kPa. As for Perkins (Table XII) and Lahoma (Table XIII), depths between 4 cm and 6 cm and 6 cm to 8 cm showed the most increase and the cone index at these depths increased by 1192 kPa and 1227 kPa respectively. Averaging the cone index values over the upper 10 cm of soil in the profile, the increases in cone index values were 1869 kPa, 1003 kPa, and 1007 kPa or 221.0%, 127.9%, and 159.9% for Haskell, Perkins, and Lahoma respectively. Again the lower percent increase in cone index values at Perkins is probably due to the trend toward higher soil moisture in grazed areas.

As expected, animal traffic does compact soil as indicated by increase in soil bulk density and soil strength found in the study conducted in Haskell, Perkins, and Lahoma. However, the depth to which differences in cone index values and soil bulk density occurred varied with location. Bulk density on the surface three centimeters changed most due to animal traffic. This concurs with Alderfer and Robinson (1947) who found cattle trampling was limited mostly to the 2.5 cm depth. In general, Van Haveren (1983), Galbraith (1971), Rauzi and Hanson (1966), Linnartz et al. (1966), and McCarty and Mazurak (1976) found that animal traffic will increase soil bulk density. Gravimetric water content was lower in areas subjected to animal traffic in Haskell and Lahoma. This can be explained by the reduction in total pore space in the soil profile which reduces the ability of water to penetrate into the profile (Linnnartz et al., 1966; Steinbrenner, 1951; Canarche et al., 1984). As discussed earlier, changes in soil strength can be attributed to changes in soil bulk density and/or soil moisture content. In Haskell and Lahoma, the increase in cone index values at the top 9 cm and 15 cm of the soil profile were the result of both soil moisture and bulk density differences. There were significant difference in both moisture content and bulk density in the top 9 cm and 15 cm and at 9 cm and 12 cm of the soil profile in these two locations respectively. However, the change in soil strength in Perkins was primarily caused by changes in bulk density since no difference in soil moisture occurred. Bryant et al. (1972) working with animal trampling made a similar conclusion for this situation.

Farmers practicing some form of conservation tillage and grazing their wheat field during fall should be concerned with animal compaction in wheat pastures. The Perkins study showed significant changes in bulk density in the top 21 cm and these differences extended down to 30 cm into the soil profile. A moldboard plow usually can till soil to a depth of 20 cm and effectively alleviate soil compaction at this depth. However, this is insufficient to alleviate all the compaction resulted from animal traffic. As mentioned earlier, compaction will accumulate over time if no efforts are taken to alleviate such compaction. Therefore, at least at some locations, the formation of "cow pan" is eminent below the depth at which soil is not disturbed by the tillage equipment. As a result, Oklahoma wheat farmers who graze their wheat fields should be familiar with the level of soil compaction from grazing activities and be knowledgeable about the types of cultural practices that can alleviate the compaction.

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APPENDIX A

SOIL TEXTURE, SOIL STRENGTH, SOIL BULK DENSITY, SOIL MOISTURE CONTENT DATA

TABLE I

SAMPLING DATES AND NUMBER OF DAYS OF GRAZING AT THE FOUR COMPACTION STUDY LOCATIONS

Location	Before Grazing	After Grazing	Days of Grazing	Animal Days* per Acre
Haskell	Oct. 29, 1986	Mar. 26, 1987	147	205
Perkins	Jan. 8, 1987	Mar. 26, 1987	55	143
Lahoma	Nov. 26, 1986	Mar. 21, 1987	75	45

* Animal Days per Acre = Number of animal per acre * number of days grazed

TABLE II

SOIL TEXTURE FOR TOP 42 CM OF SOIL PROFILE AT HASKELL

Depth	Sand	Silt	Clay	Soil texture
cm	----------	%	----------	
0 - 3	34.72	55.28	10.00	Silt loam
3 - 6	30.53	58.22	11.25	Silt loam
6 - 9	25.47	59.53	15.00	Silt loam
9 - 12	28.79	61.96	9.25	Silt loam
12 - 15	26.03	61.47	12.50	Silt loam
15 - 18	27.71	63.04	9.25	Silt loam
18 - 21	23.27	67.47	9.25	Silt loam
21 - 24	24.88	65.87	9.25	Silt loam
24 - 27	24.88	60.64	14.48	Silt loam
27 - 30	23.27	59.62	17.10	Silt loam
30 - 33	21.89	57.07	21.04	Silt loam
33 - 36	22.50	53.84	23.66	Silt loam
36 - 39	23.27	51.75	24.97	Silt loam
39 - 42	20.50	50.58	28.92	Clay loam

TABLE III

SOIL TEXTURE FOR TOP 42 CM OF SOIL PROFILE AT PERKINS

Depth	Sand	Silt	Clay	Soil Texture
cm	----------	%	----------	
0 - 3	61.97	26.78	11.25	Sandy loam
3 - 6	62.15	26.60	11.25	Sandy loam
6 - 9	61.97	24.28	13.75	Sandy loam
9 - 12	64.67	24.08	11.25	Sandy loam
12 - 15	64.67	24.08	11.25	Sandy loam
15 - 18	65.91	22.84	11.25	Sandy loam
18 - 21	63.28	25.47	11.25	Sandy loam
21 - 24	63.18	24.62	12.20	Sandy loam
24 - 27	63.05	23.20	13.75	Sandy loam
27 - 30	65.69	21.81	12.50	Sandy loam
30 - 33	60.71	25.54	13.75	Sandy loam
33 - 36	59.42	24.33	16.25	Sandy loam
36 - 39	71.05	15.20	13.75	Sandy loam
39 - 42	56.47	26.30	17.24	Sandy loam

TABLE IV

SOIL TEXTURE FOR TOP 42 CM OF SOIL PROFILE AT LAHOMA

Depth	Sand	Silt	Clay	Soil Texture
cm	----------	%	----------	
0 - 3	24.78	59.24	15.98	Silt loam
3 - 6	24.78	58.97	16.25	Silt loam
6 - 9	24.22	59.53	16.25	Silt loam
9 - 12	23.63	57.62	18.75	Silt loam
12 - 15	23.63	58.87	17.50	Silt loam
15 - 18	24.78	58.97	16.25	Silt loam
18 - 21	23.63	57.62	18.75	Silt loam
21 - 24	18.11	54.39	27.50	Silty clay loam
24 - 27	20.00	55.00	25.00	Silt loam
27 - 30	19.39	55.61	25.00	Silt loam
30 - 33	18.76	56.24	25.00	Silt loam
33 - 36	50.16	31.09	18.75	Loam
36 - 39	18.00	55.75	26.25	Silt loam
39 - 42	17.26	55.24	27.50	Silty clay loam

TABLE V

EFFECT OF GRAZING ON SOIL MOISTURE CONTENT AT HASKELL

	------- Moisture Content -------			
Depth	Grazed	Ungrazed	Difference[1]	LSD[2]
cm	------------- % --------------			
0 - 3	19.29	20.62	- 1.33	*[3]
3 - 6	17.97	20.11	- 2.14	*
6 - 9	18.09	19.60	- 1.51	*
9 - 12	18.40	19.24	- 0.84	NS
12 - 15	18.57	19.65	- 1.08	NS
15 - 18	19.09	19.91	- 0.82	NS
18 - 21	19.89	20.48	- 0.59	NS
21 - 24	20.42	21.13	- 0.71	NS
24 - 27	21.07	21.54	- 0.47	NS
27 - 30	21.97	22.01	- 0.04	NS
30 - 33	22.42	21.85	0.57	NS
33 - 36	22.45	21.98	0.47	NS
36 - 39	22.75	22.29	0.46	NS
39 - 42	23.62	22.71	0.91	NS

[1] Grazed minus Ungrazed.
[2] Least Significant Difference at 5 percent.
[3] *, NS = Significant or Not Significant at 5 percent.

TABLE VI

EFFECT OF GRAZING ON SOIL MOISTURE CONTENT AT LAHOMA

	------- Moisture Content -------			
Depth	Grazed	Ungrazed	Difference[1]	LSD[2]
cm	------------- % -------------			
0 - 3	19.59	20.54	- 1.95	*[3]
3 - 6	18.86	20.91	- 2.05	*
6 - 9	18.63	20.27	- 1.64	*
9 - 12	18.54	21.01	- 2.47	*
12 - 15	18.75	20.43	- 1.68	*
15 - 18	19.33	20.59	- 1.26	NS
18 - 21	19.84	20.47	- 0.63	NS
21 - 24	20.83	20.97	- 0.14	NS
24 - 27	21.15	21.26	- 0.11	NS
27 - 30	21.19	21.16	0.03	NS
30 - 33	21.05	21.18	- 0.13	NS
33 - 36	20.96	21.02	- 0.06	NS
36 - 39	20.70	20.93	- 0.23	NS
39 - 42	20.42	20.59	- 0.17	NS

[1] Grazed minus Ungrazed.

[2] Least Significant Difference at 5 percent.

[3] *, NS = Significant or Not Significant at 5 percent.

TABLE VII

EFFECT OF GRAZING ON SOIL MOISTURE CONTENT AT PERKINS

	------- Moisture Content -------			
Depth	Grazed	Ungrazed	Difference[1]	LSD[2]
cm	------------- % --------------			
0 - 3	12.53	12.76	- 0.23	NS[3]
3 - 6	13.33	12.89	0.44	NS
6 - 9	13.47	12.92	0.55	NS
9 - 12	13.94	12.48	1.46	NS
12 - 15	14.33	12.98	1.35	NS
15 - 18	14.37	13.28	1.09	NS
18 - 21	14.63	13.28	1.35	NS
21 - 24	14.91	13.91	1.00	NS
24 - 27	15.17	14.48	0.69	NS
27 - 30	15.41	14.00	1.41	NS
30 - 33	15.71	14.15	1.56	NS
33 - 36	15.74	14.61	1.13	NS
36 - 39	15.85	14.41	1.44	NS
39 - 42	15.92	14.70	1.22	NS

[1] Grazed minus Ungrazed.
[2] Least Significant Difference at 5 percent.
[3] *, NS = Significant or Not Significant at 5 percent.

TABLE VIII

EFFECT OF GRAZING ON SOIL BULK DENSITY AT HASKELL

	---------- Bulk Density ----------			
Depth	Grazed	Ungrazed	Difference[1]	LSD[2]
cm	----------	g cc^{-1}	----------	
0 - 3	1.574	1.362	0.212	*[3]
3 - 6	1.557	1.387	0.170	*
6 - 9	1.542	1.445	0.097	*
9 - 12	1.500	1.480	0.020	NS
12 - 15	1.484	1.482	0.002	NS
15 - 18	1.499	1.471	0.028	NS
18 - 21	1.473	1.481	- 0.008	NS
21 - 24	1.461	1.480	- 0.019	NS
24 - 27	1.457	1.454	0.003	NS
27 - 30	1.443	1.451	- 0.008	NS
30 - 33	1.444	1.443	0.001	NS
33 - 36	1.474	1.464	0.010	NS
36 - 39	1.491	1.460	0.031	NS
39 - 42	1.526	1.468	0.058	*

[1] Grazed minus Ungrazed.
[2] Least Significant Difference at 5 percent.
[3] *, NS = Significant or Not significant at 5 percent.

TABLE IX

EFFECT OF GRAZING ON SOIL BULK DENSITY AT PERKINS

	Bulk Density			
Depth	Grazed	Ungrazed	Difference[1]	LSD[2]
cm	$g\ cc^{-1}$			
0 - 3	1.749	1.503	0.246	*[3]
3 - 6	1.785	1.583	0.202	*
6 - 9	1.741	1.616	0.125	*
9 - 12	1.711	1.604	0.107	*
12 - 15	1.684	1.572	0.112	*
15 - 18	1.680	1.606	0.074	*
18 - 21	1.707	1.624	0.083	*
21 - 24	1.697	1.659	0.038	NS
24 - 27	1.666	1.607	0.059	NS
27 - 30	1.625	1.586	0.039	NS
30 - 33	1.621	1.614	0.007	NS
33 - 36	1.632	1.608	0.024	NS
36 - 39	1.638	1.634	0.004	NS
39 - 42	1.659	1.650	0.009	NS

[1] Grazed minus Ungrazed.

[2] Least Significant Difference at 5 percent.

[3] *, NS = Significant or Not Significant at 5 percent.

TABLE X

EFFECT OF GRAZING ON SOIL BULK DENSITY AT LAHOMA

Depth	Bulk Density			LSD[2]
	Grazed	Ungrazed	Difference[1]	
cm	g cc^{-1}			
0 - 3	1.553	1.349	0.204	*[3]
3 - 6	1.545	1.401	0.144	*
6 - 9	1.543	1.427	0.116	*
9 - 12	1.525	1.465	0.060	*
12 - 15	1.496	1.469	0.027	NS
15 - 18	1.483	1.463	0.020	NS
18 - 21	1.497	1.468	0.029	NS
21 - 24	1.457	1.464	- 0.007	NS
24 - 27	1.425	1.400	0.025	NS
27 - 30	1.394	1.375	0.019	NS
30 - 33	1.376	1.362	0.014	NS
33 - 36	1.353	1.353	0.000	NS
36 - 39	1.348	1.344	0.004	NS
39 - 42	1.380	1.342	0.038	NS

[1] Grazed minus Ungrazed.
[2] Least Significant Difference at 5 percent.
[3] *, NS = Significant or Not Significant at 5 percent.

TABLE XI

EFFECT OF GRAZING ON SOIL STRENGTH AT HASKELL

	---------- Cone Index ----------			
Depth	Grazed[1]	Ungrazed[2]	Difference[3]	LSD[4]
cm	------------ kPa ------------			
0 - 2	2572.1	665.0	1907.1	*[5]
2 - 4	2977.4	799.1	2178.3	*
4 - 6	2943.5	857.3	2086.2	*
6 - 8	2751.2	980.0	1771.2	*
8 - 10	2560.2	1154.8	1405.4	*
10 - 12	2417.4	1348.3	1069.1	*
12 - 14	2334.6	1528.8	805.8	*
14 - 16	2310.0	1647.1	612.9	*
16 - 18	2302.8	1863.4	439.4	NS
18 - 20	2280.7	1996.7	284.0	NS
20 - 22	2239.5	2065.9	173.6	NS
22 - 24	2224.9	2107.2	117.7	NS
24 - 26	2158.8	2143.1	15.7	NS
26 - 28	2114.9	2141.0	- 26.1	NS
28 - 30	2028.2	2126.0	- 97.8	NS
30 - 32	1928.0	2082.5	- 154.5	NS
32 - 34	1894.4	2047.4	- 153.0	NS
34 - 36	1870.7	2115.6	- 244.9	NS
36 - 38	1830.9	2196.4	- 365.5	NS
38 - 40	1777.7	2140.4	- 362.7	NS
40 - 42	1699.3	2034.7	- 335.4	NS

1 & 2 Mean average of cone index for grazed and ungrazed.
3 Grazed minus Ungrazed.
4 Least Significant Difference at 5 percent.
5 *, NS = Significant or Not Significant at 5 percent.

TABLE XII

EFFECT OF GRAZING ON SOIL STRENGTH AT PERKINS

	---------- Cone Index ----------			
Depth	Grazed[1]	Ungrazed[2]	Difference[3]	LSD[4]
cm	------------ kPa ------------			
0 - 2	1161.2	571.7	589.5	*[5]
2 - 4	1667.0	693.6	973.4	*
4 - 6	1972.9	780.4	1192.5	*
6 - 8	2077.0	885.3	1191.7	*
8 - 10	2050.6	981.9	1068.7	*
10 - 12	1929.0	1038.4	890.6	*
12 - 14	1775.6	1096.0	679.6	*
14 - 16	1665.4	1124.2	541.2	*
16 - 18	1581.6	1116.0	465.6	*
18 - 20	1511.1	1087.5	423.6	*
20 - 22	1480.9	1032.1	448.8	*
22 - 24	1468.2	1002.8	465.4	*
24 - 26	1460.7	982.8	477.9	*
26 - 28	1498.1	1009.7	488.4	*
28 - 30	1588.9	1142.5	446.4	*
30 - 32	1700.0	1395.5	304.5	NS
32 - 34	1829.4	1676.1	153.3	NS
34 - 36	1990.9	1910.9	80.0	NS
36 - 38	2093.5	2113.8	- 20.3	NS
38 - 40	2103.1	2239.9	- 136.8	NS
40 - 42	2110.4	2353.1	- 242.7	NS

1 & 2 Mean average of cone index for grazed and ungrazed.
3 Grazed minus ungrazed.
4 Least Significant Difference at 5 percent.
5 *, NS = Significant or Not significant 5 percent.

TABLE XIII

EFFECT OF GRAZING ON SOIL STRENGTH AT LAHOMA

	---------- Cone Index ----------			
Depth	Grazed[1]	Ungrazed[2]	Difference[3]	LSD[4]
cm	------------ kPa ------------			
0 - 2	1170.4	432.0	738.4	*[5]
2 - 4	1382.0	545.8	836.2	*
4 - 6	1810.5	653.4	1157.1	*
6 - 8	1957.5	730.1	1227.4	*
8 - 10	1906.0	826.5	1079.5	*
10 - 12	1839.2	923.3	915.9	*
12 - 14	1806.0	996.0	810.0	*
14 - 16	1798.5	1044.0	754.5	*
16 - 18	1800.1	1096.8	703.3	*
18 - 20	1868.8	1159.7	709.1	*
20 - 22	1992.3	1240.2	752.1	*
22 - 24	2063.9	1292.9	771.0	*
24 - 26	2094.0	1382.3	711.7	*
26 - 28	2023.4	1430.0	593.4	*
28 - 30	1830.4	1447.7	382.7	*
30 - 32	1593.5	1443.7	149.8	NS
32 - 34	1409.0	1408.4	0.6	NS
34 - 36	1317.2	1325.6	- 8.4	NS
36 - 38	1254.4	1218.8	35.6	NS
38 - 40	1202.6	1184.5	18.1	NS
40 - 42	1162.2	1170.4	- 8.2	NS

1 & 2 Mean average of cone index for grazed and ungrazed.
3 Grazed minus Ungrazed.
4 Least Significant Difference at 5 percent.
5 *, NS = Significant or Not significant at 5 percent.

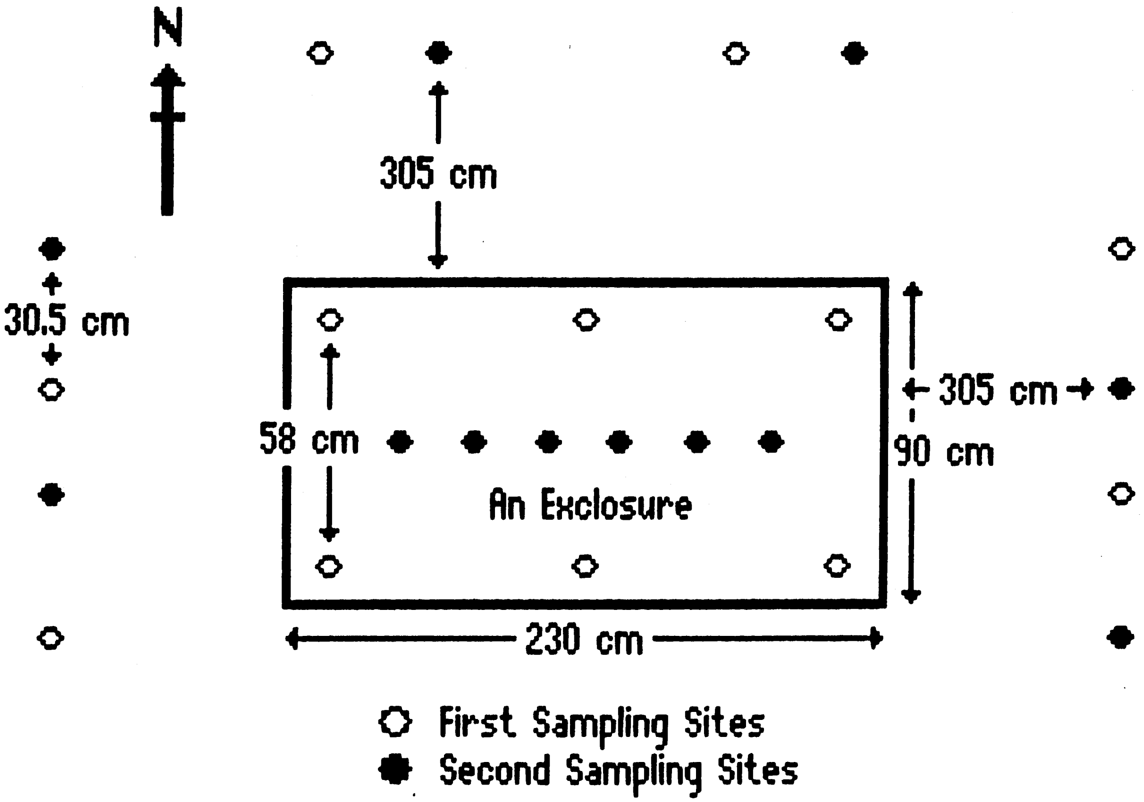

Figure 1. Layout of sampling sites for first and second sampling dates in a replication.

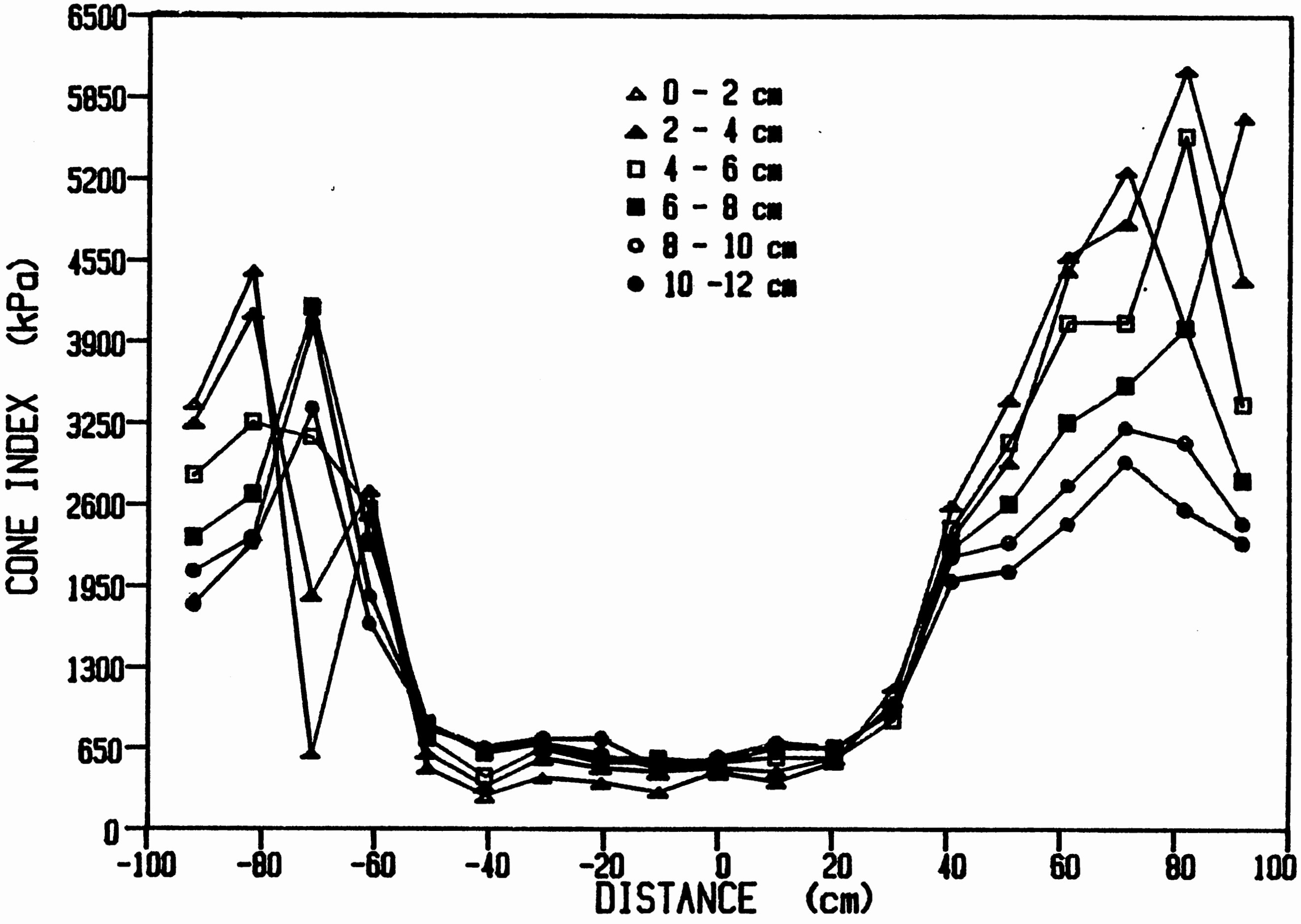

Figure 2. Compaction pattern of the top 12 cm of soil profile across an exclosure at Lahoma.

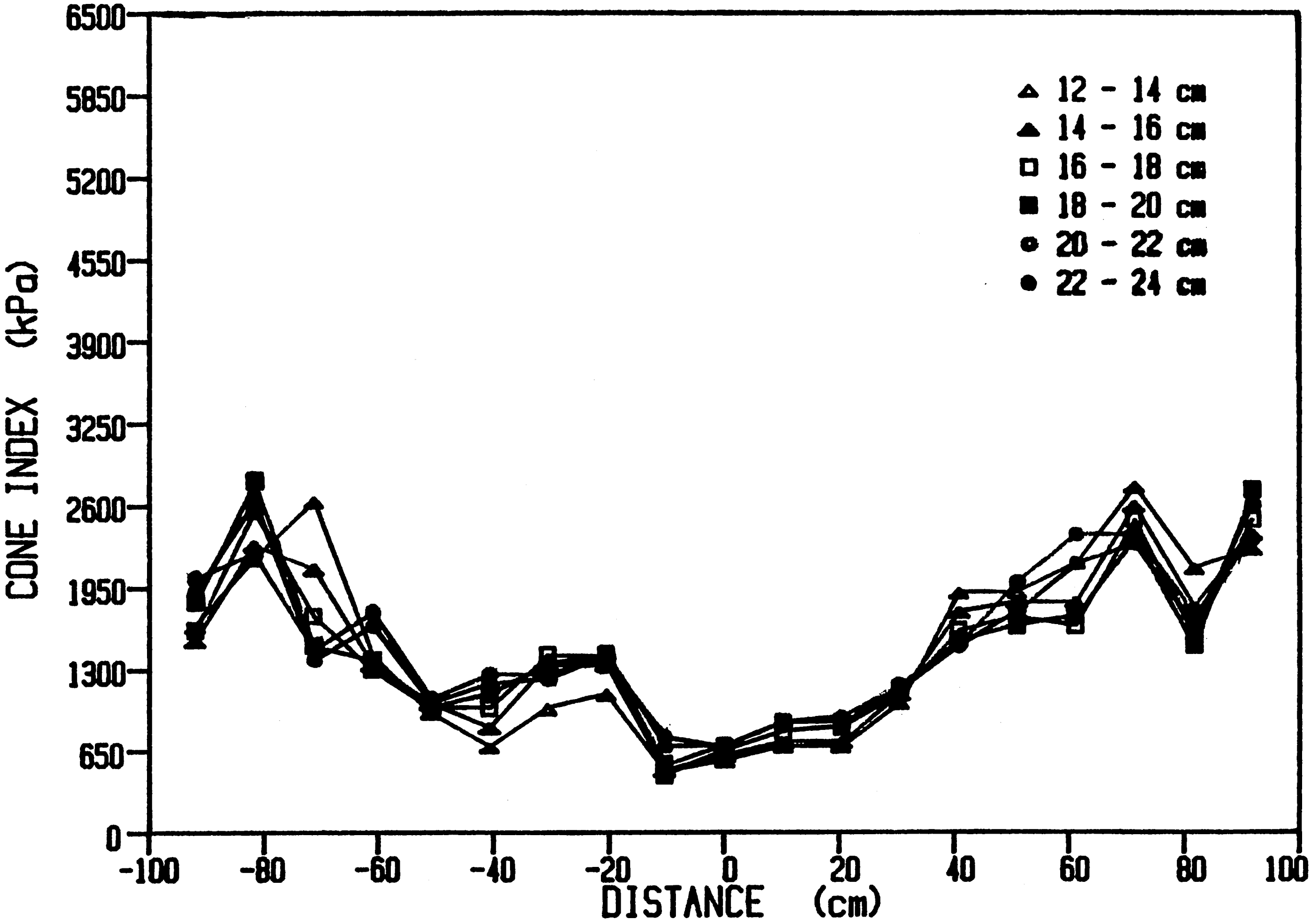

Figure 3. Compaction pattern of depth between 12 cm and 24 cm of soil profile across an exclosure at Lahoma.

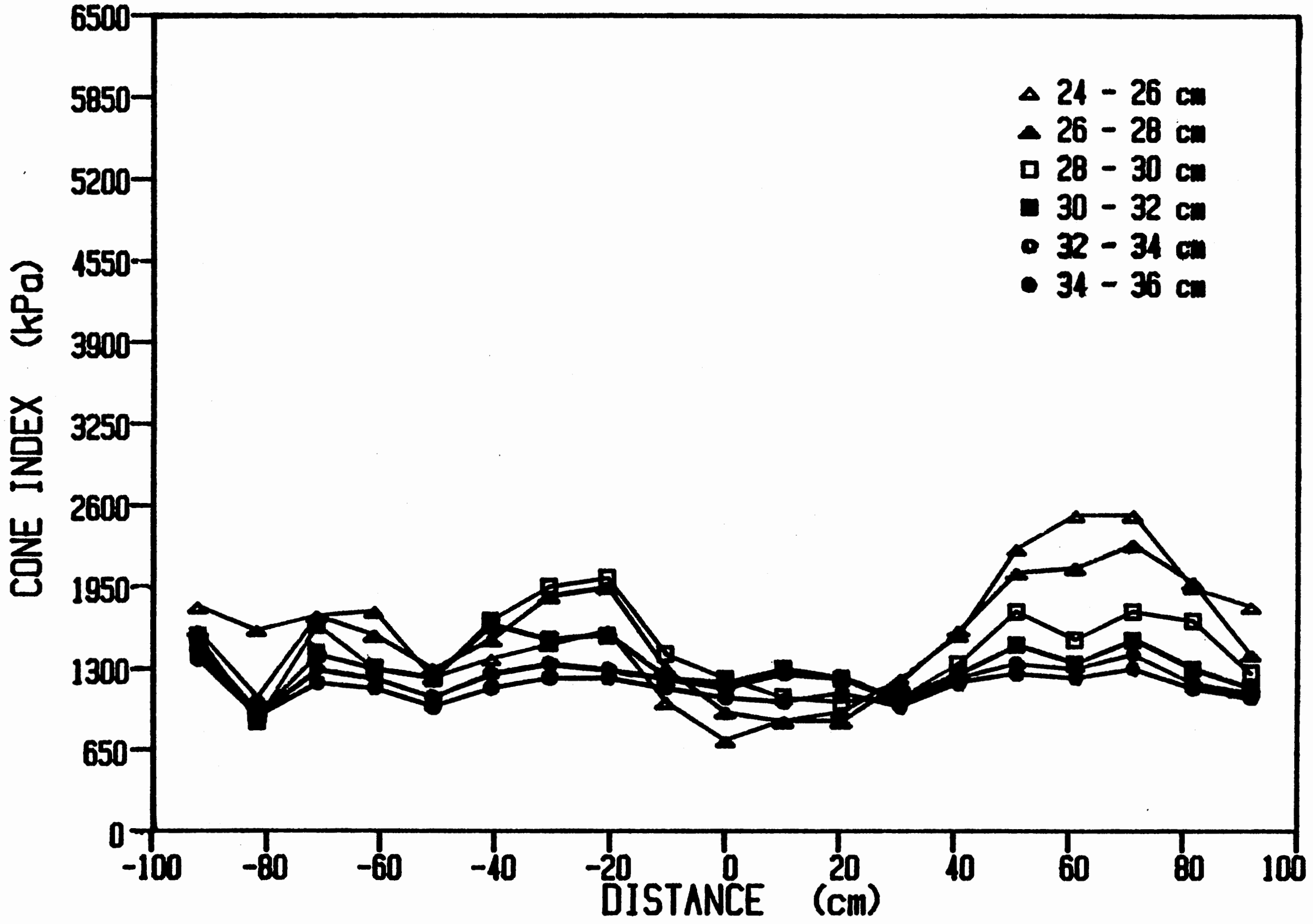

Figure 4. Compaction pattern of depth between 24 cm and 36 cm of soil profile across an exclosure at Lahoma.

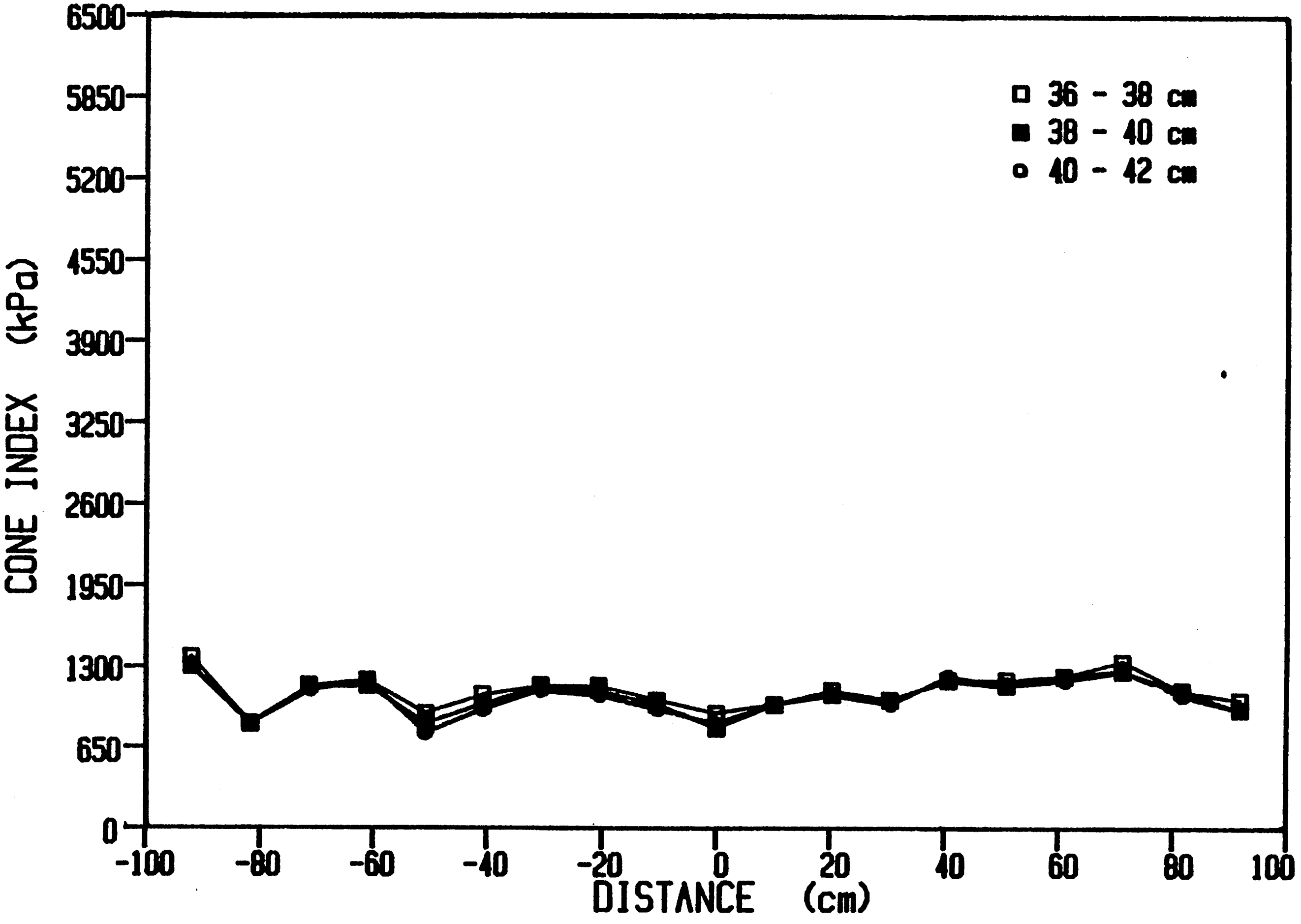

Figure 5. Compaction pattern of depth between 36 cm and 42 cm of soil profile across an exclosure at Lahoma.

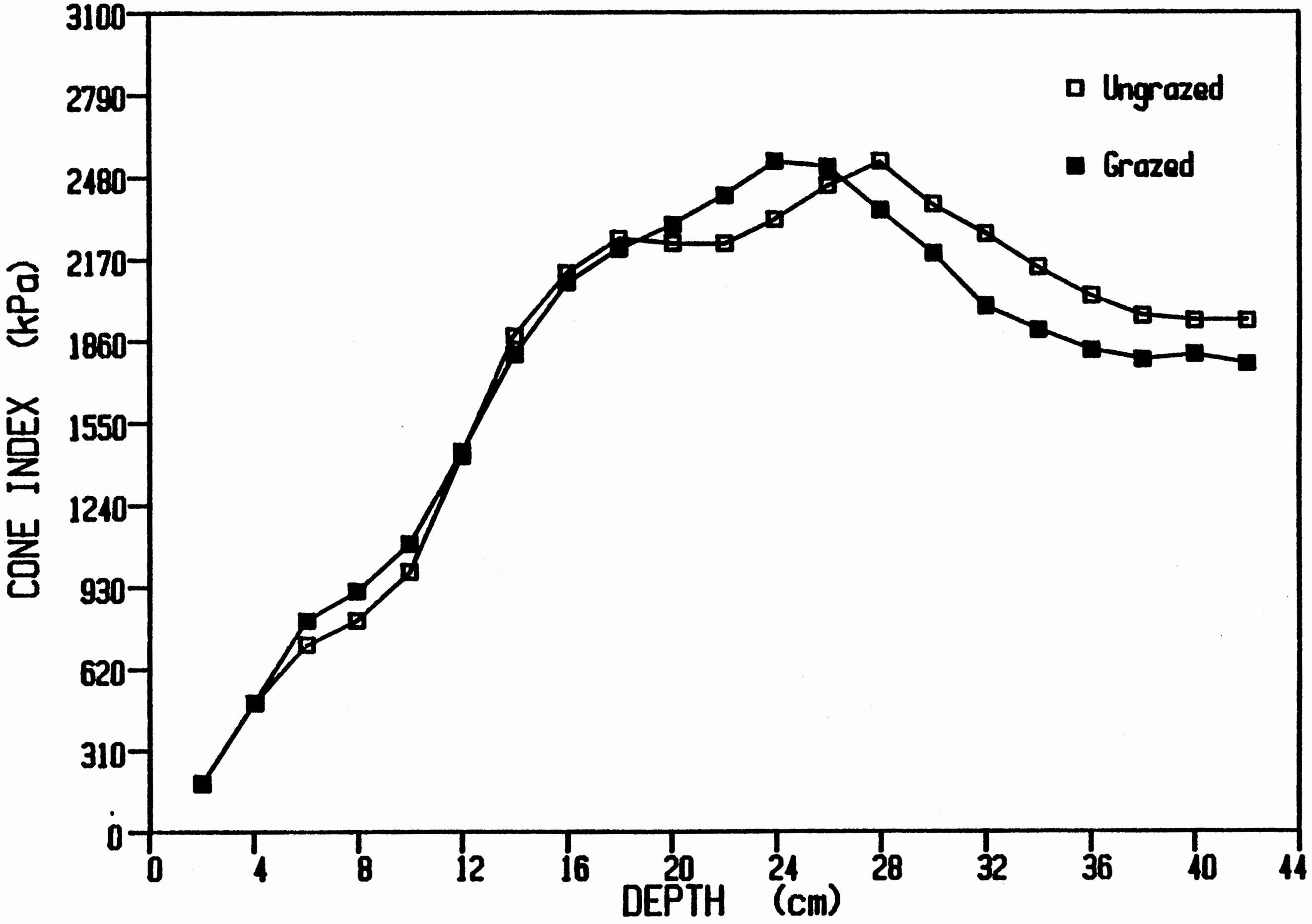

Figure 6. Soil strength for grazed and ungrazed areas at Haskell before grazing.

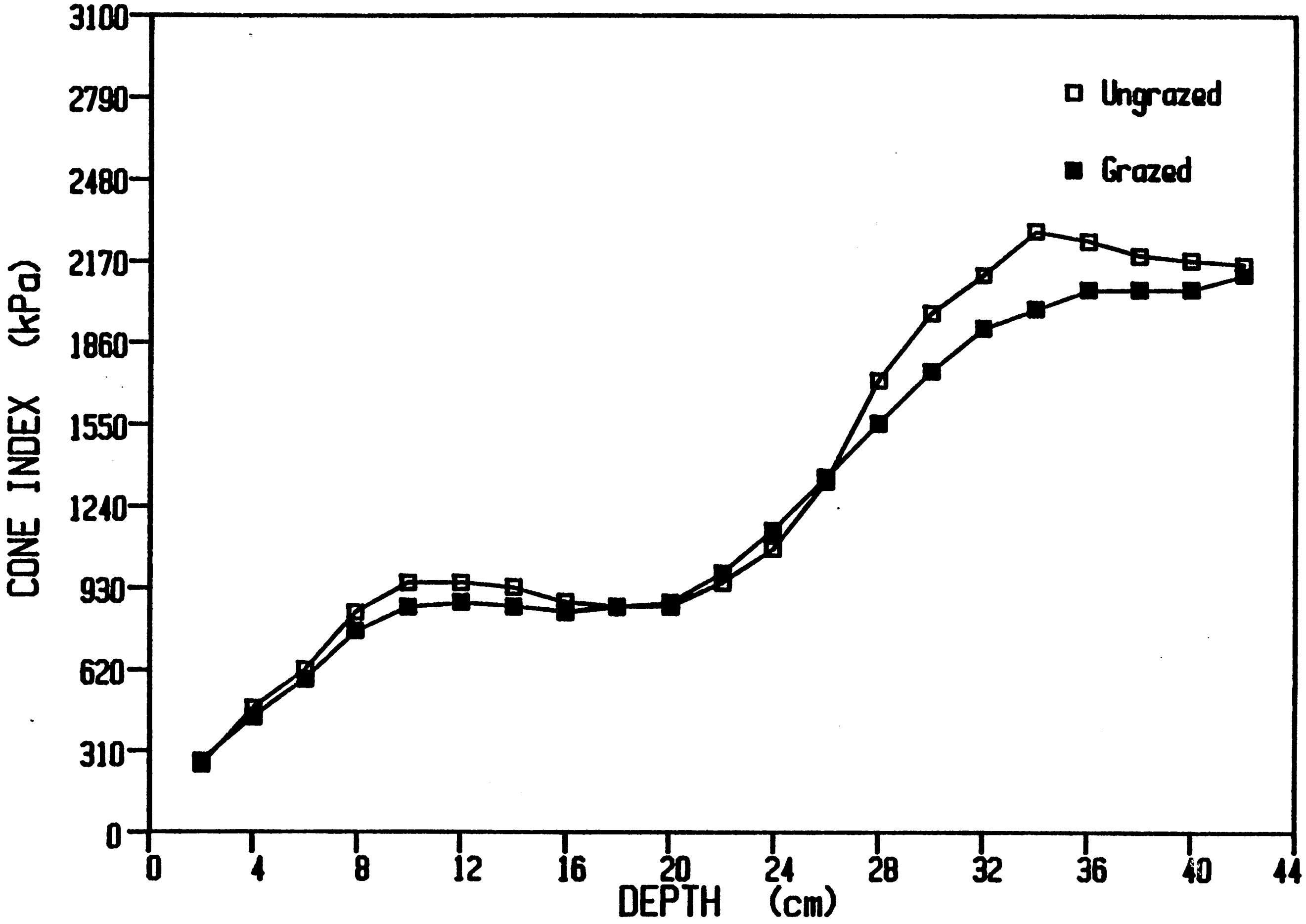

Figure 7. Soil strength for grazed and ungrazed areas at Perkins before grazing.

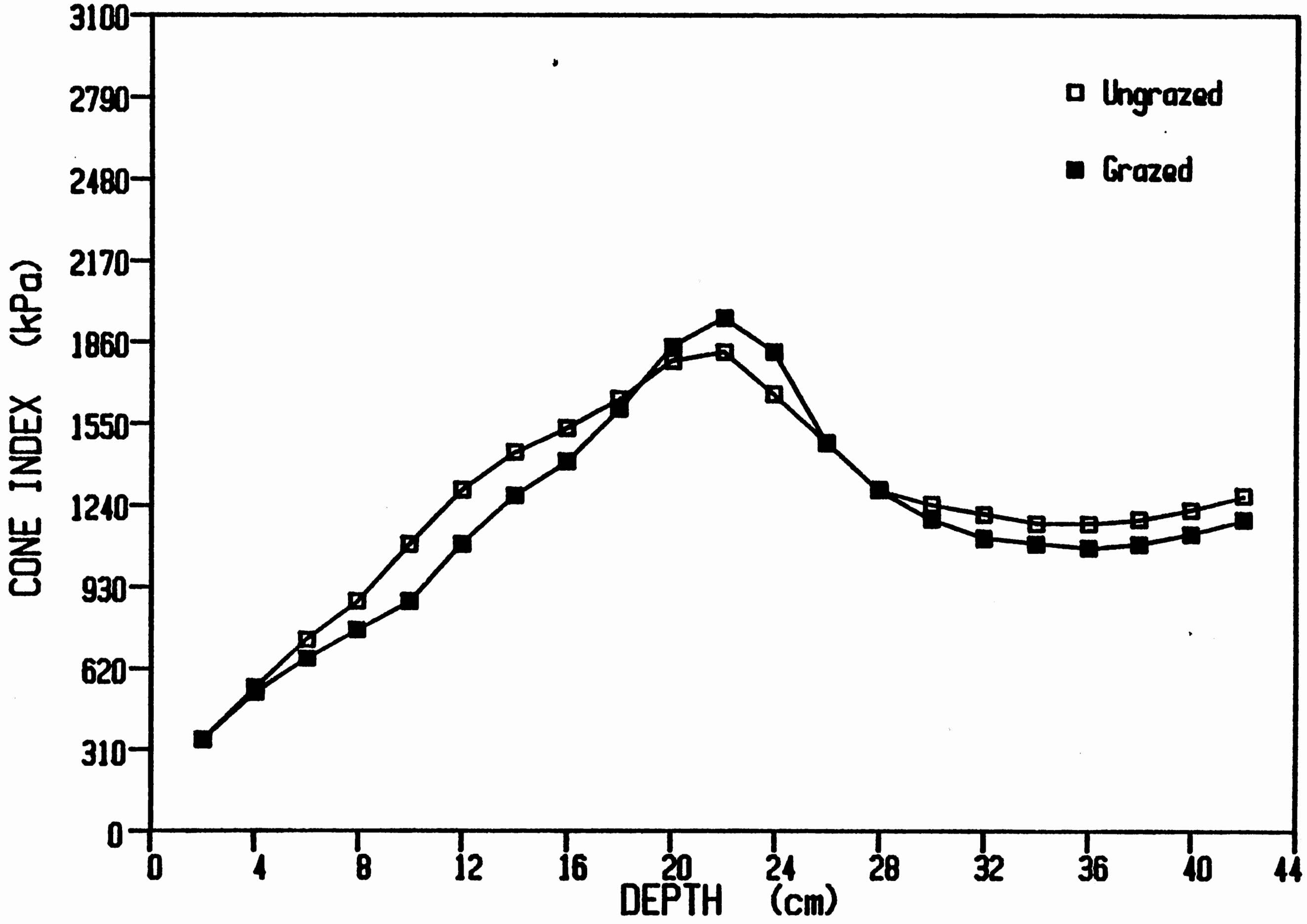

Figure 8. Soil strength for grazed and ungrazed areas at Lahoma before grazing.

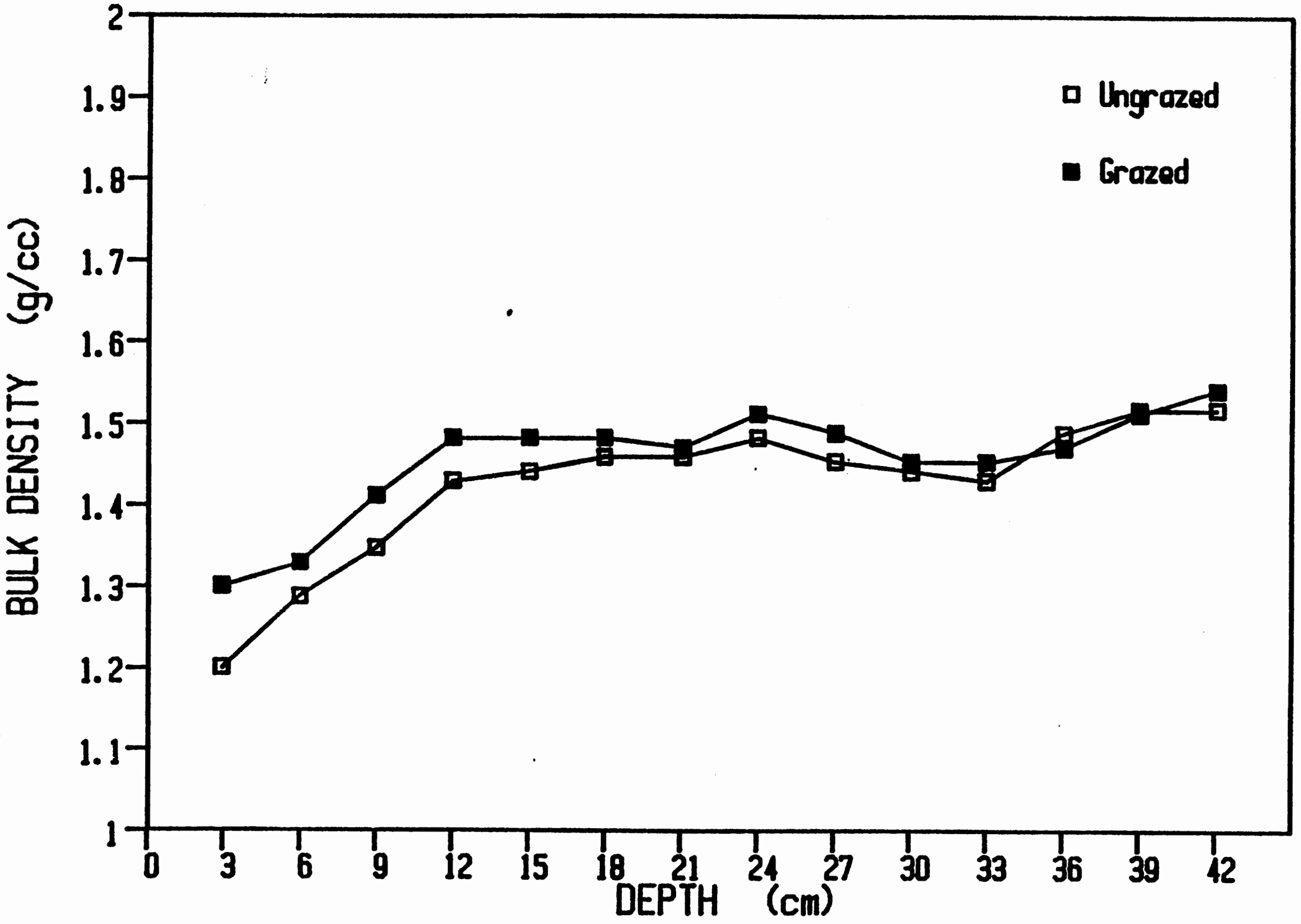

Figure 9. Bulk density for grazed and ungrazed areas at Haskell before grazing.

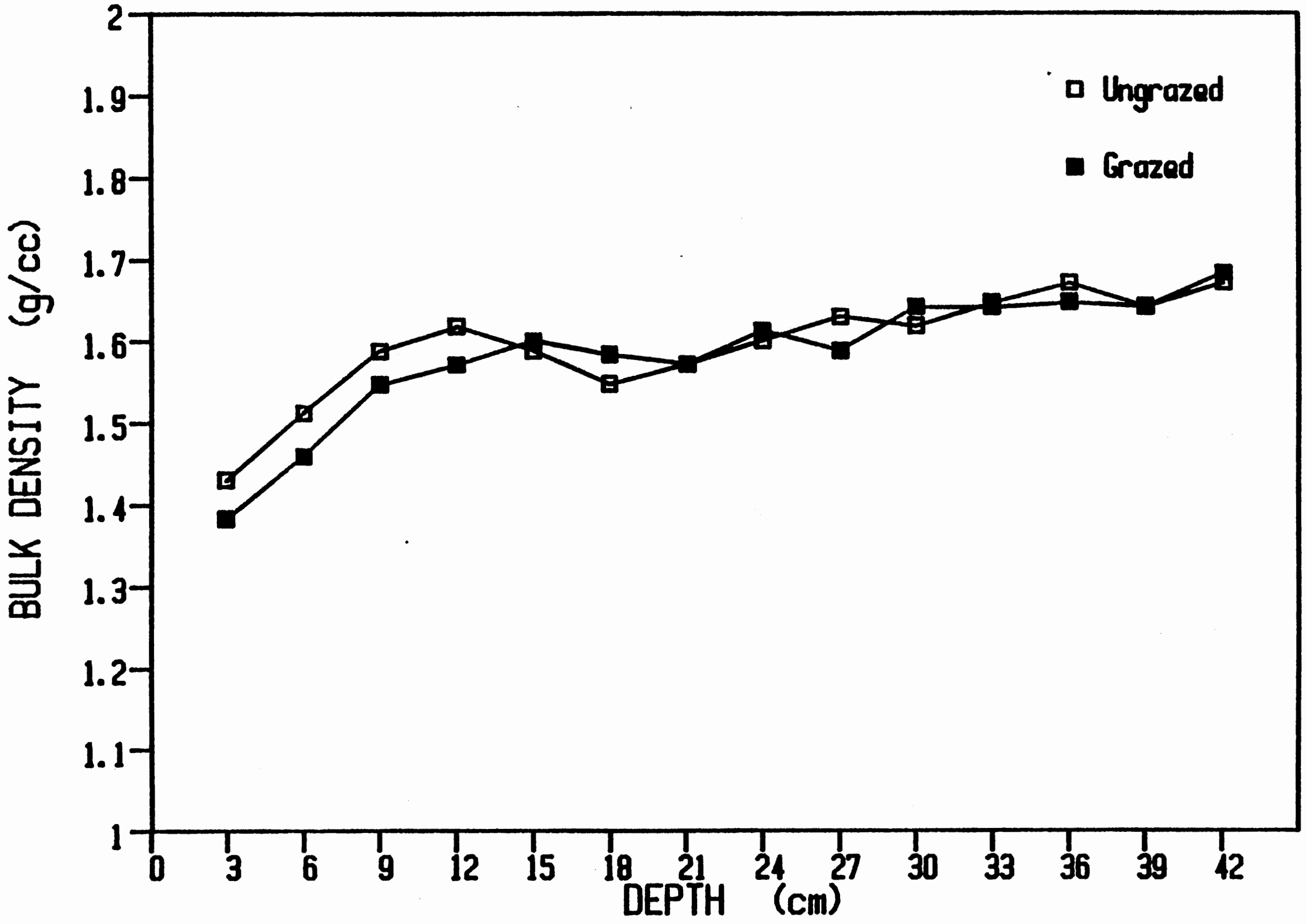

Figure 10. Bulk density for grazed and ungrazed areas at Perkins before grazing.

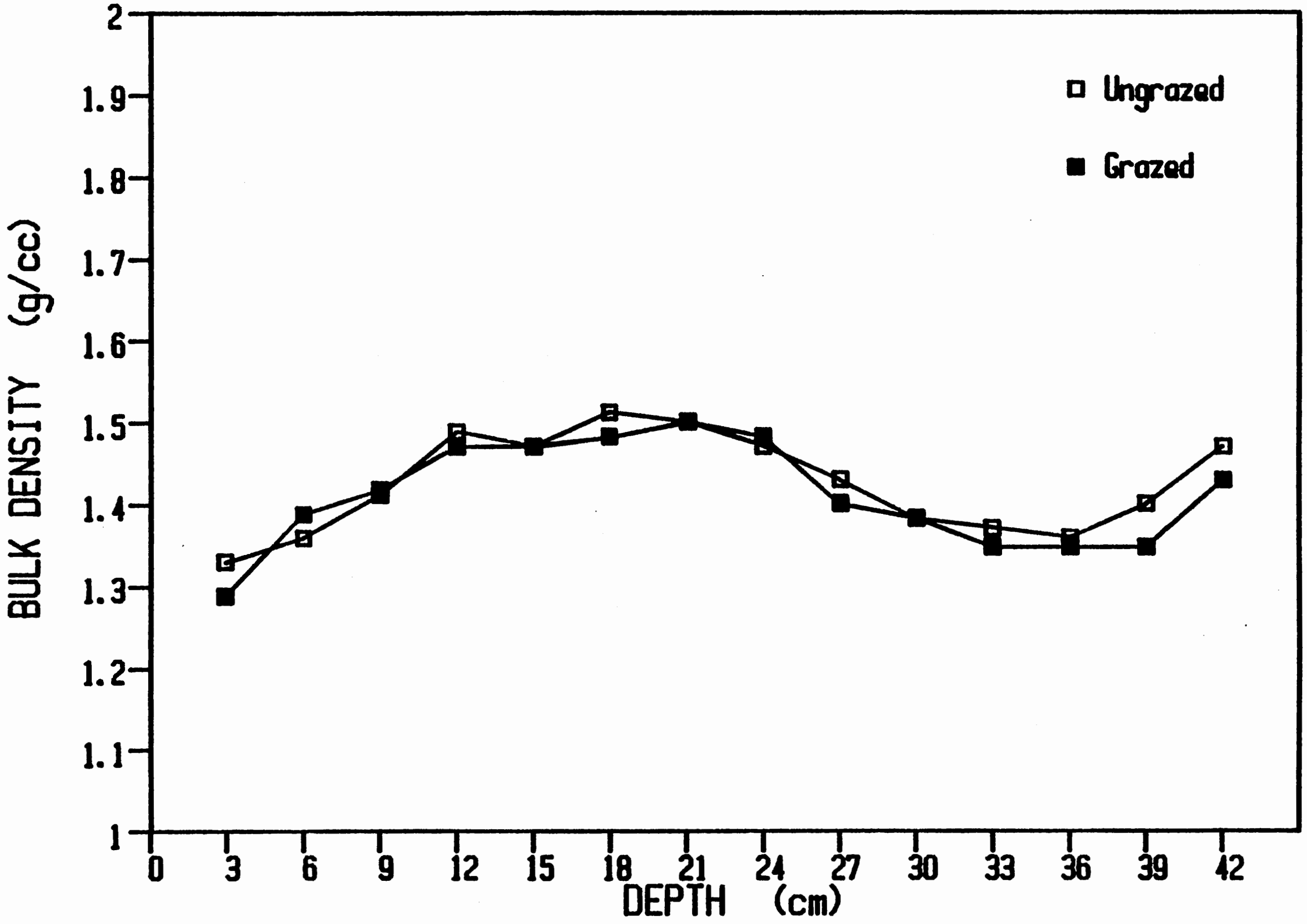

Figure 11. Bulk density for grazed and ungrazed areas at Lahoma before grazing.

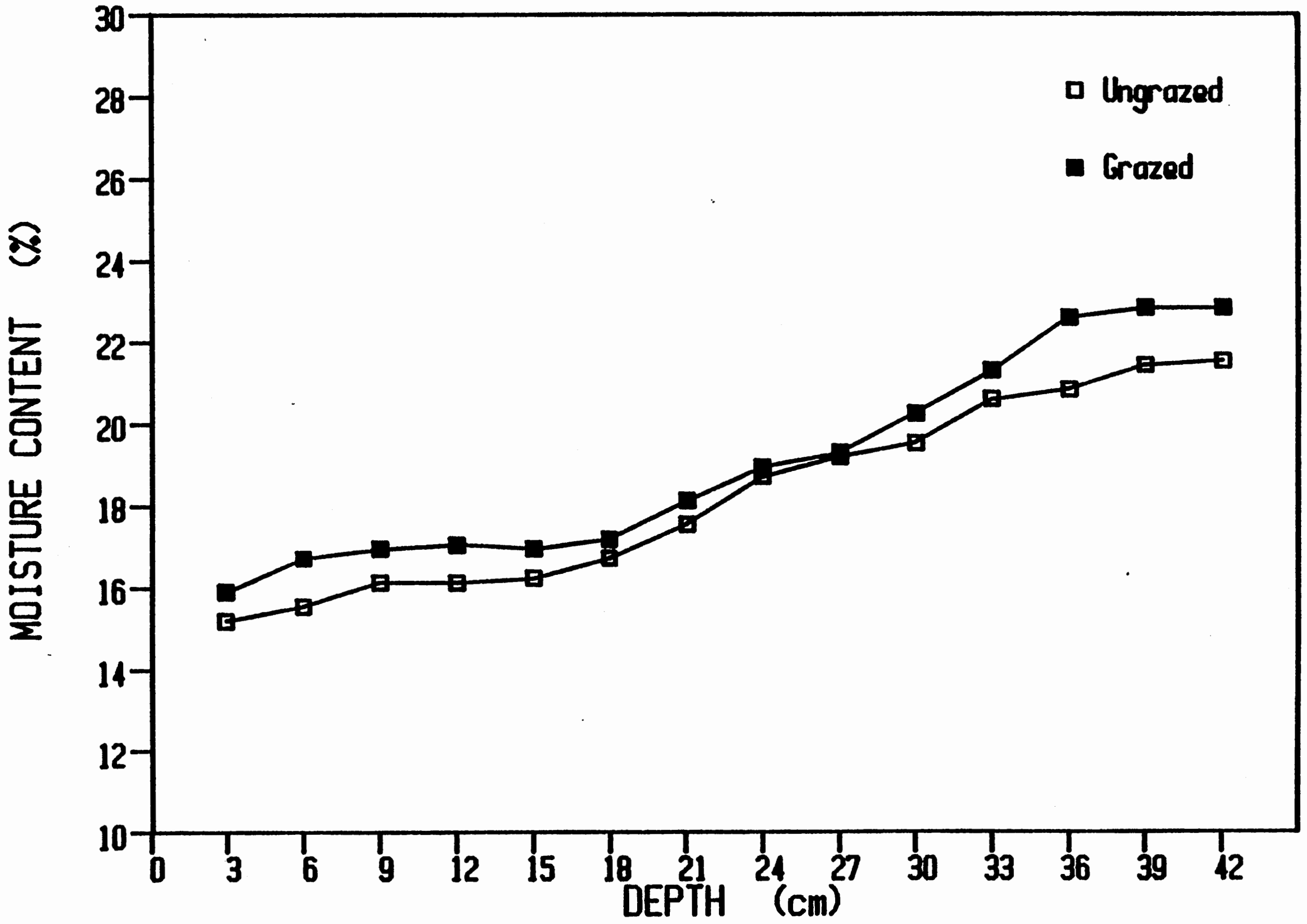

Figure 12. Gravimetric water content for grazed and ungrazed areas at Haskell before grazing.

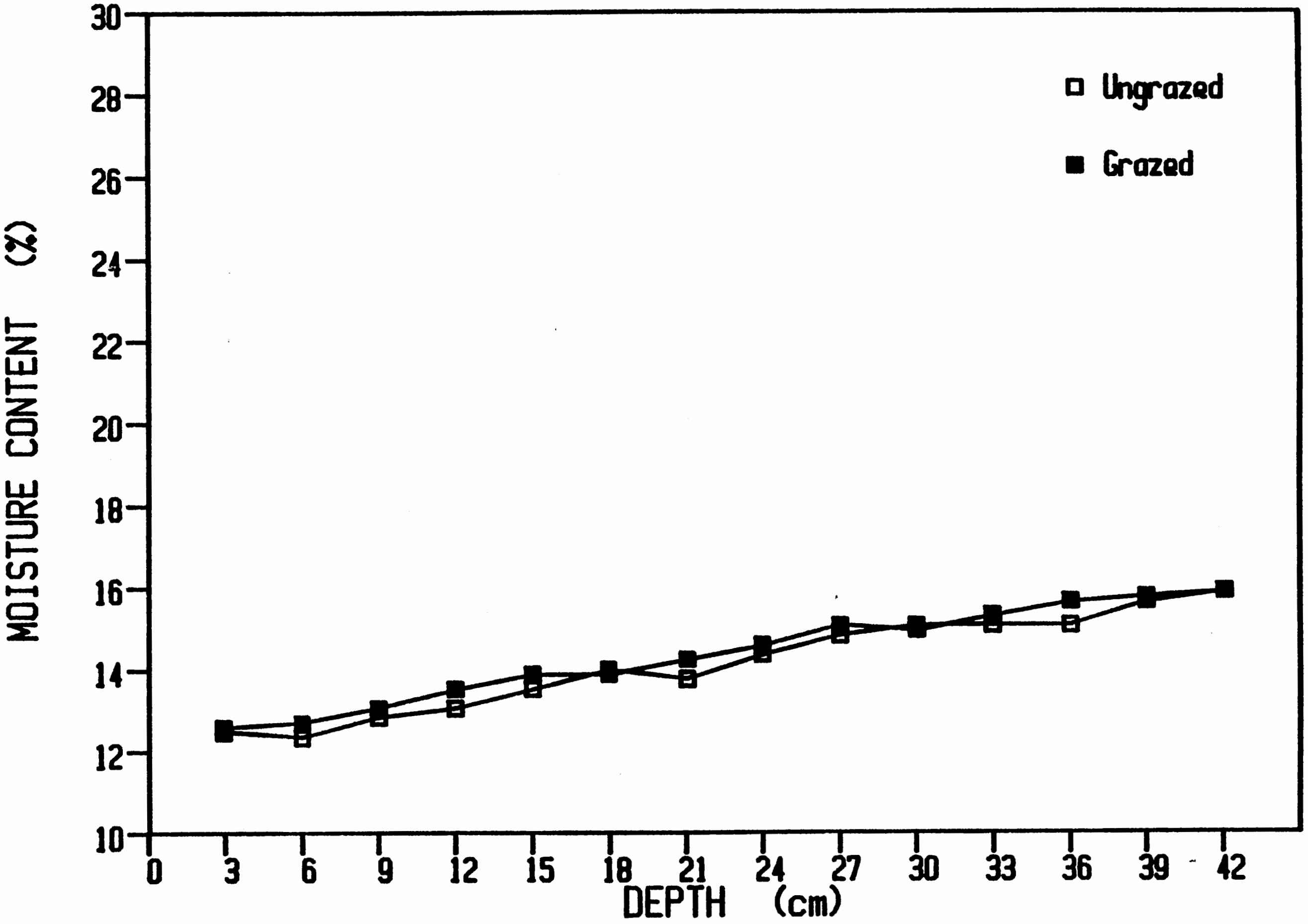

Figure 13. Gravimetric water content for grazed and ungrazed areas at Perkins before grazing.

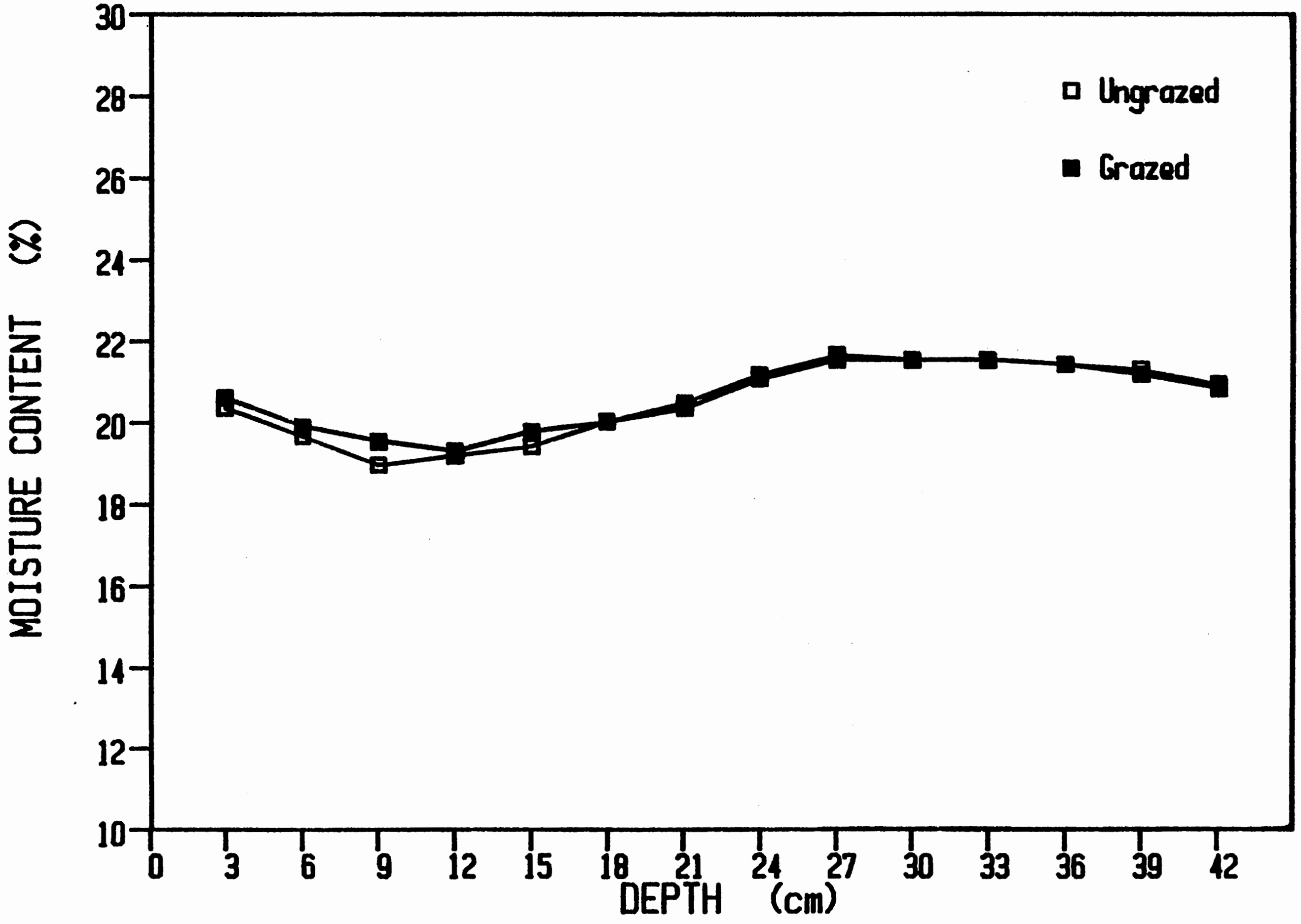

Figure 14. Gravimetric water content for grazed and ungrazed areas at Lahoma before grazing.

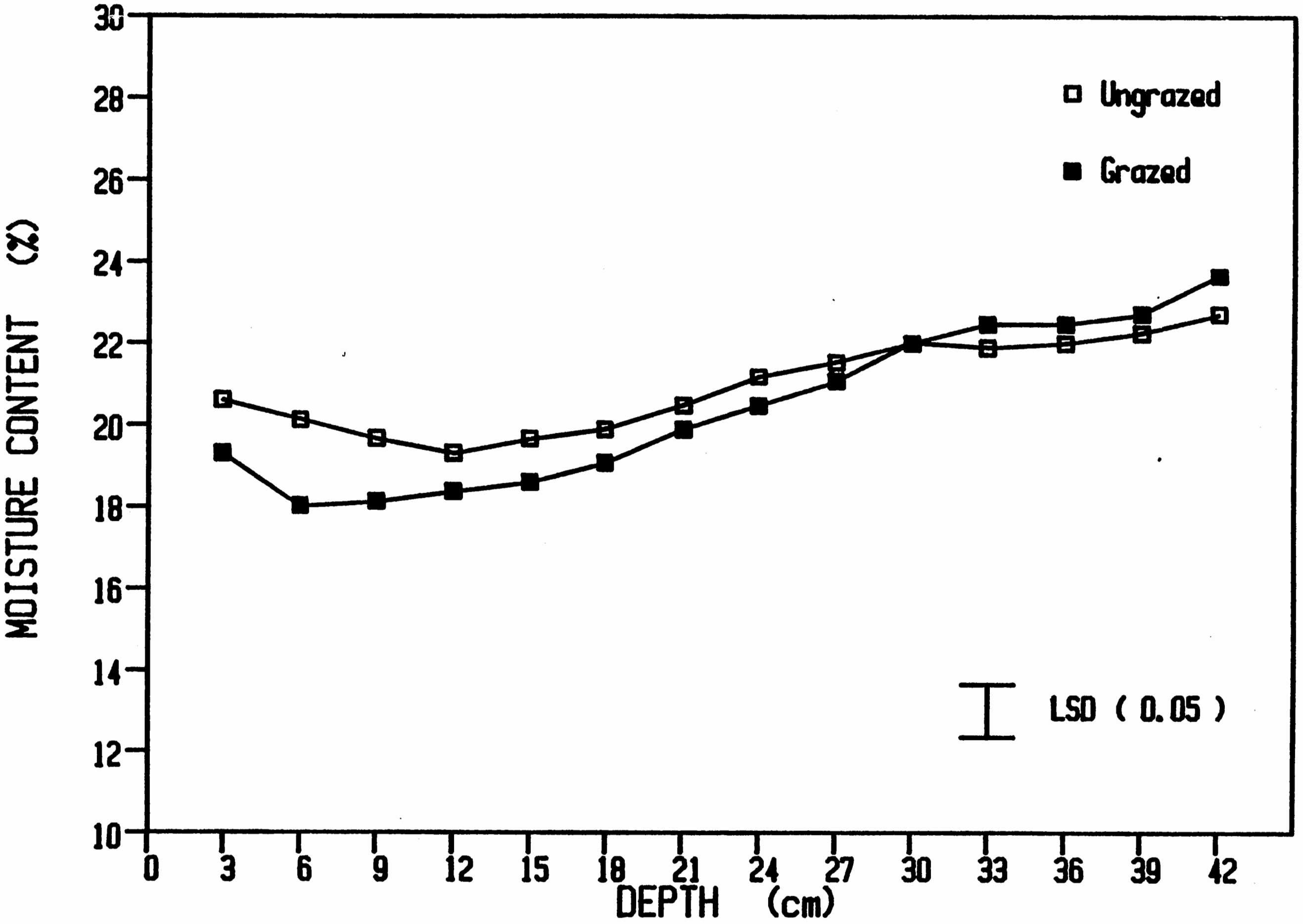

Figure 15. Gravimetric water content for grazed and ungrazed areas at Haskell after grazing.

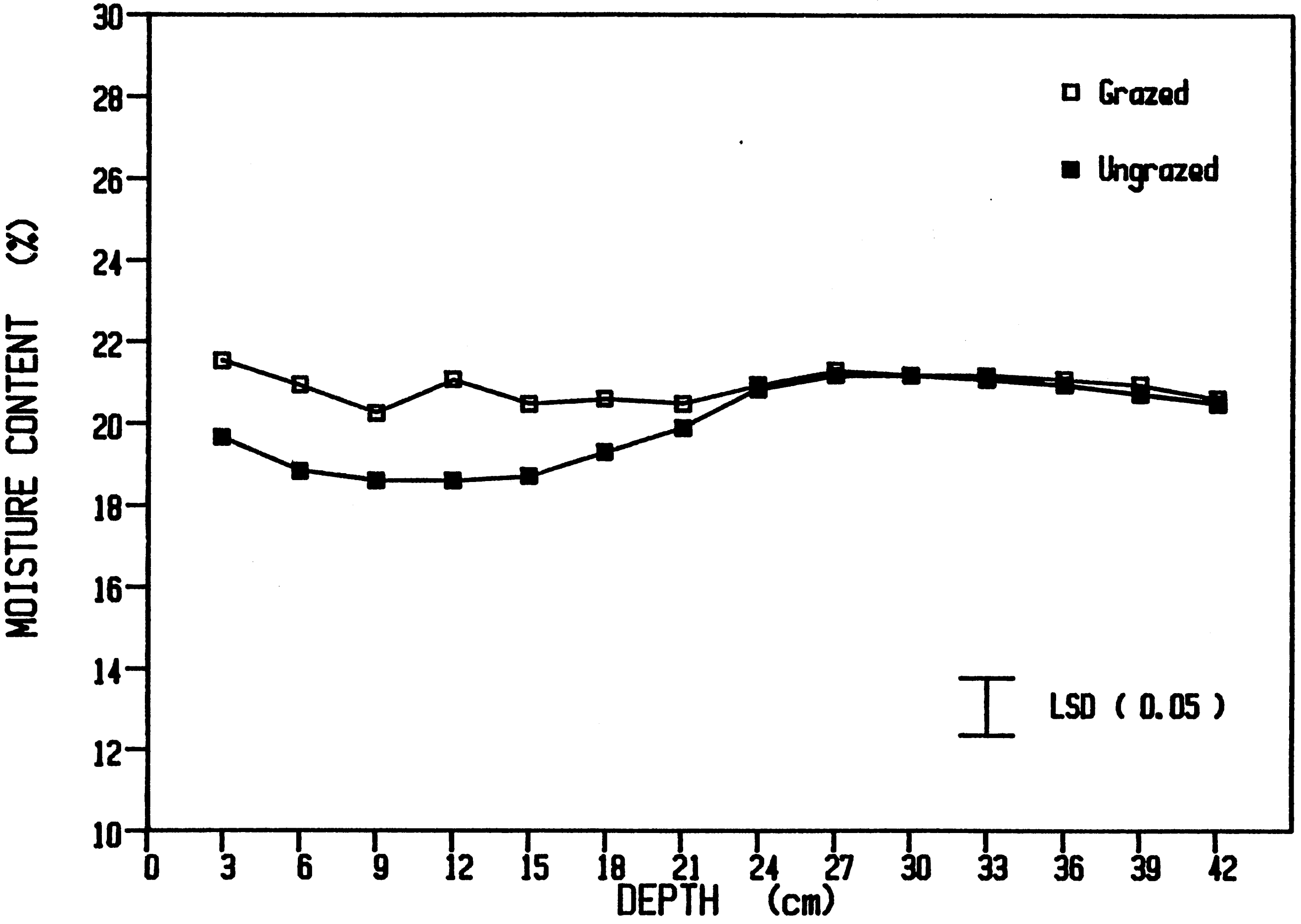

Figure 16. Gravimetric water content for grazed and ungrazed areas at Lahoma after grazing.

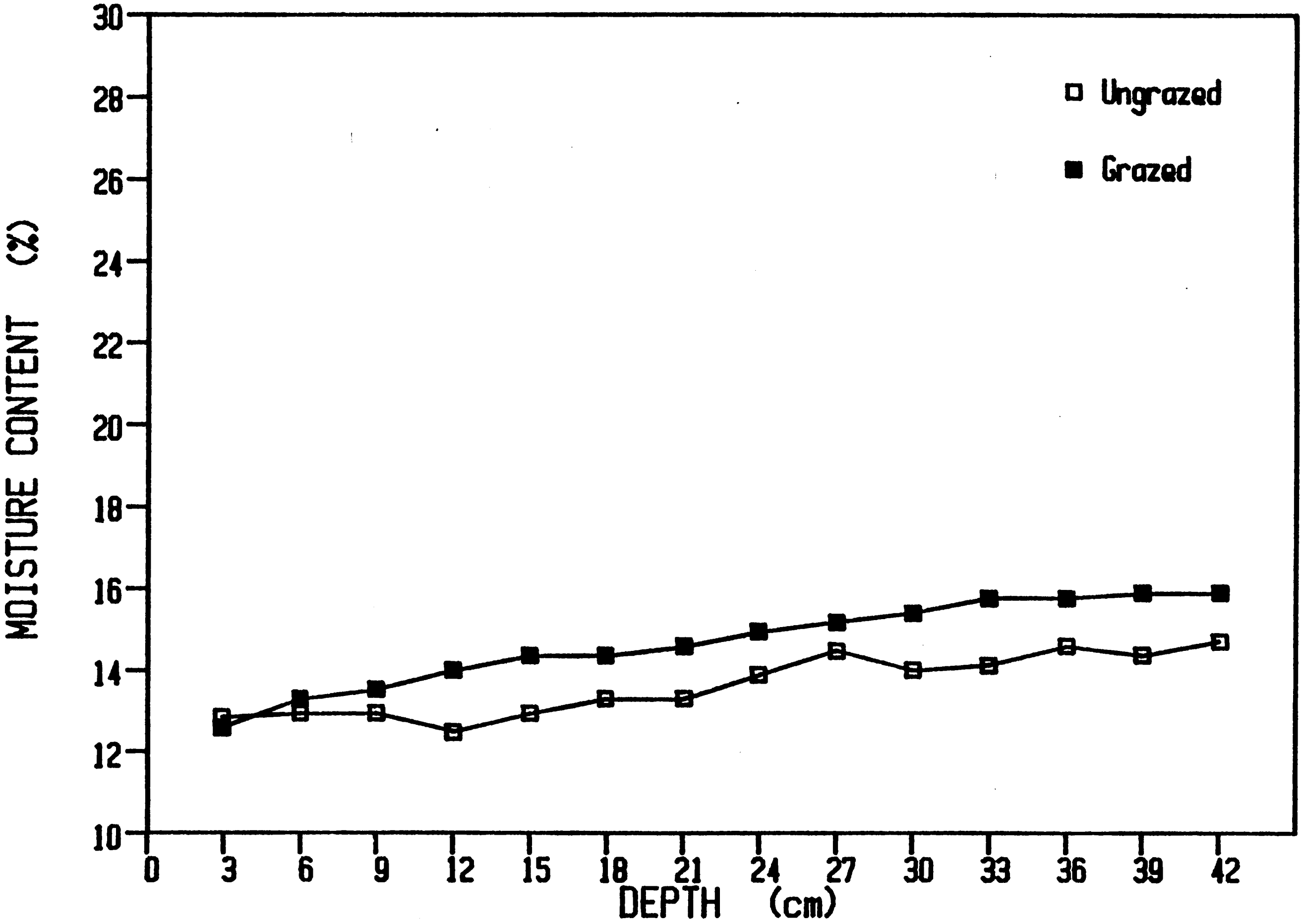

Figure 17. Gravimetric water content for grazed and ungrazed areas at Perkins after grazing.

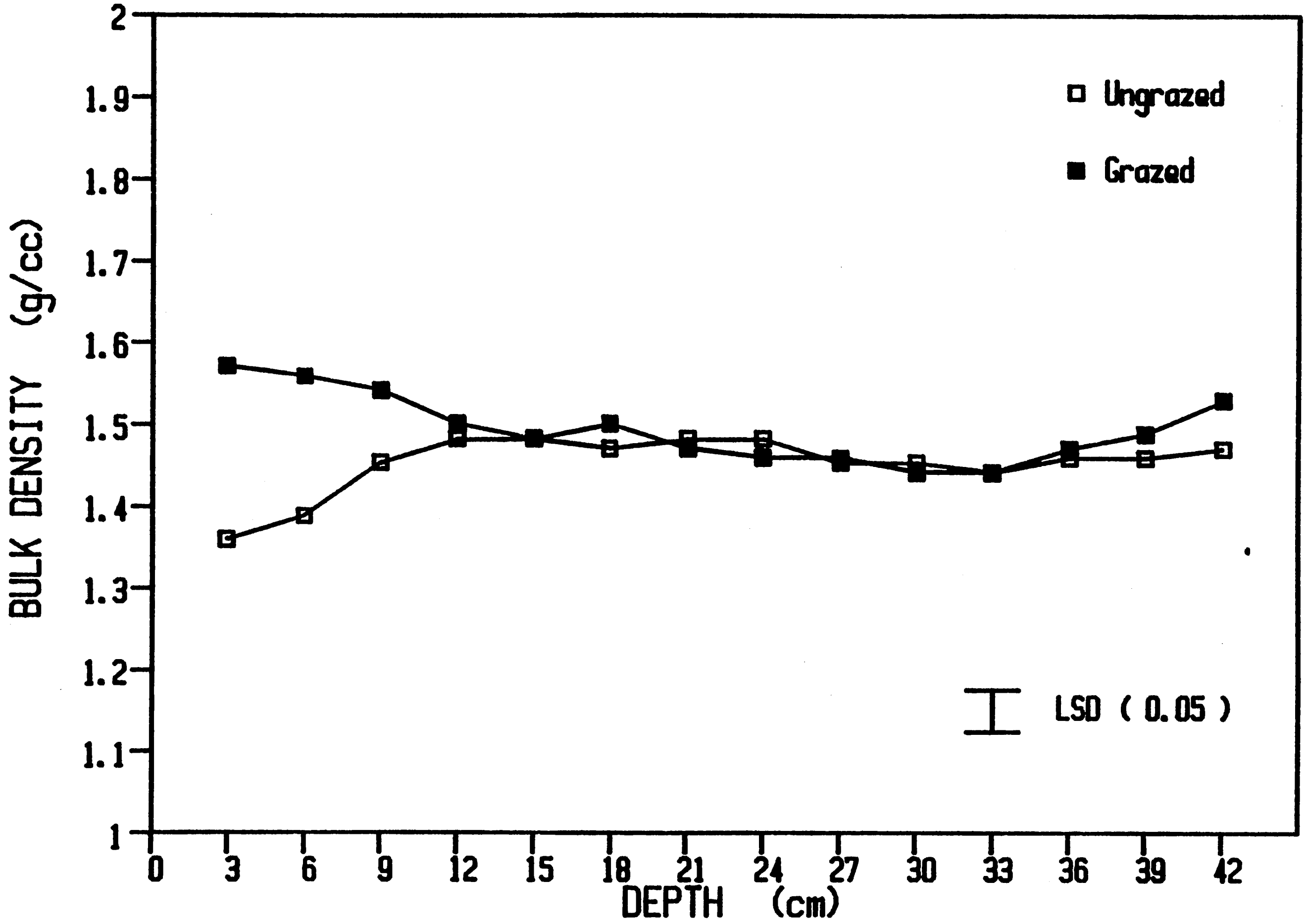

Figure 18. Bulk density for grazed and ungrazed areas at Haskell after grazing.

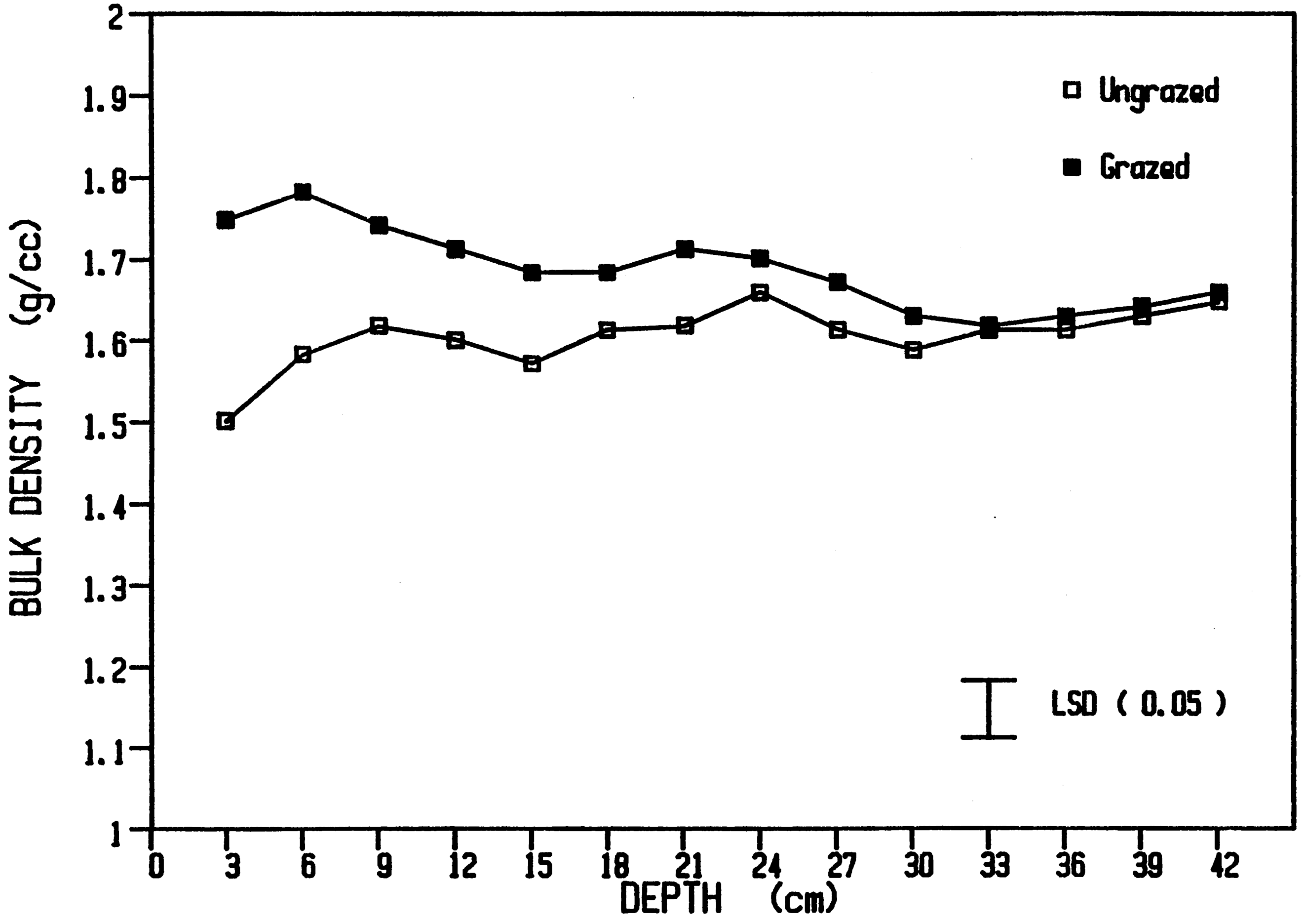

Figure 19. Bulk density for grazed and ungrazed areas at Perkins after grazing.

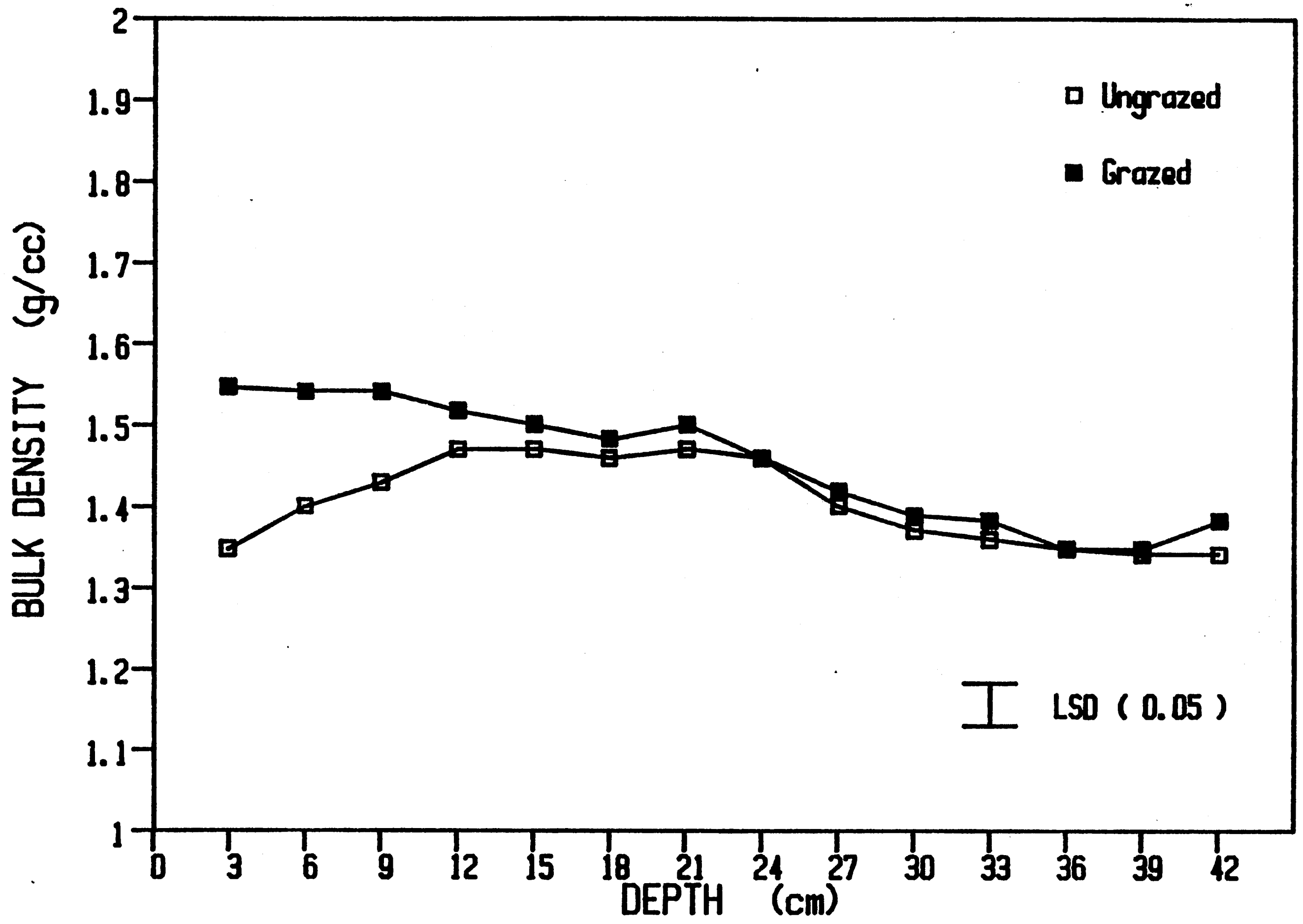

Figure 20. Bulk density for grazed and ungrazed areas at Lahoma after grazing.

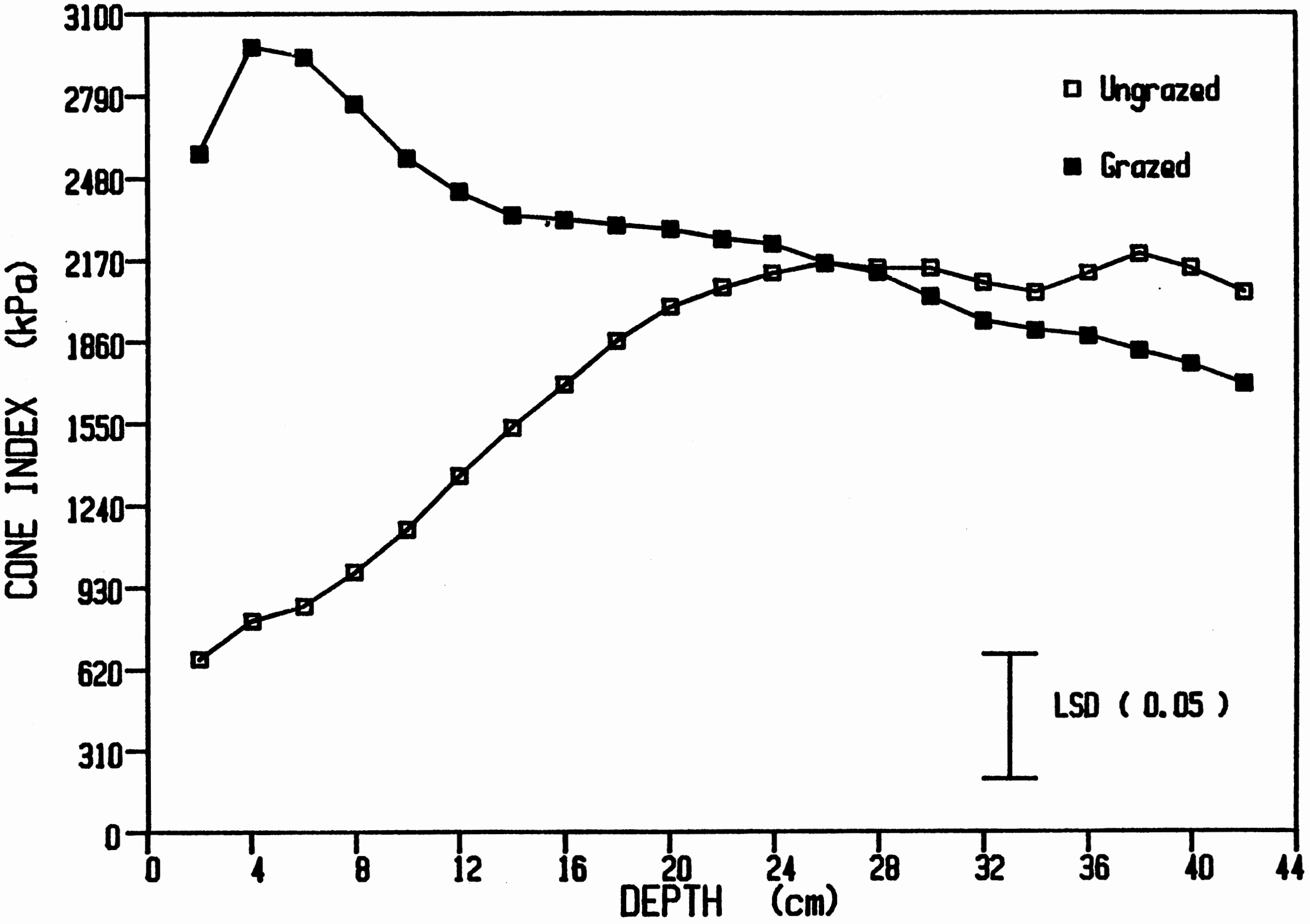

Figure 21. Soil strength for grazed and ungrazed areas at Haskell after grazing.

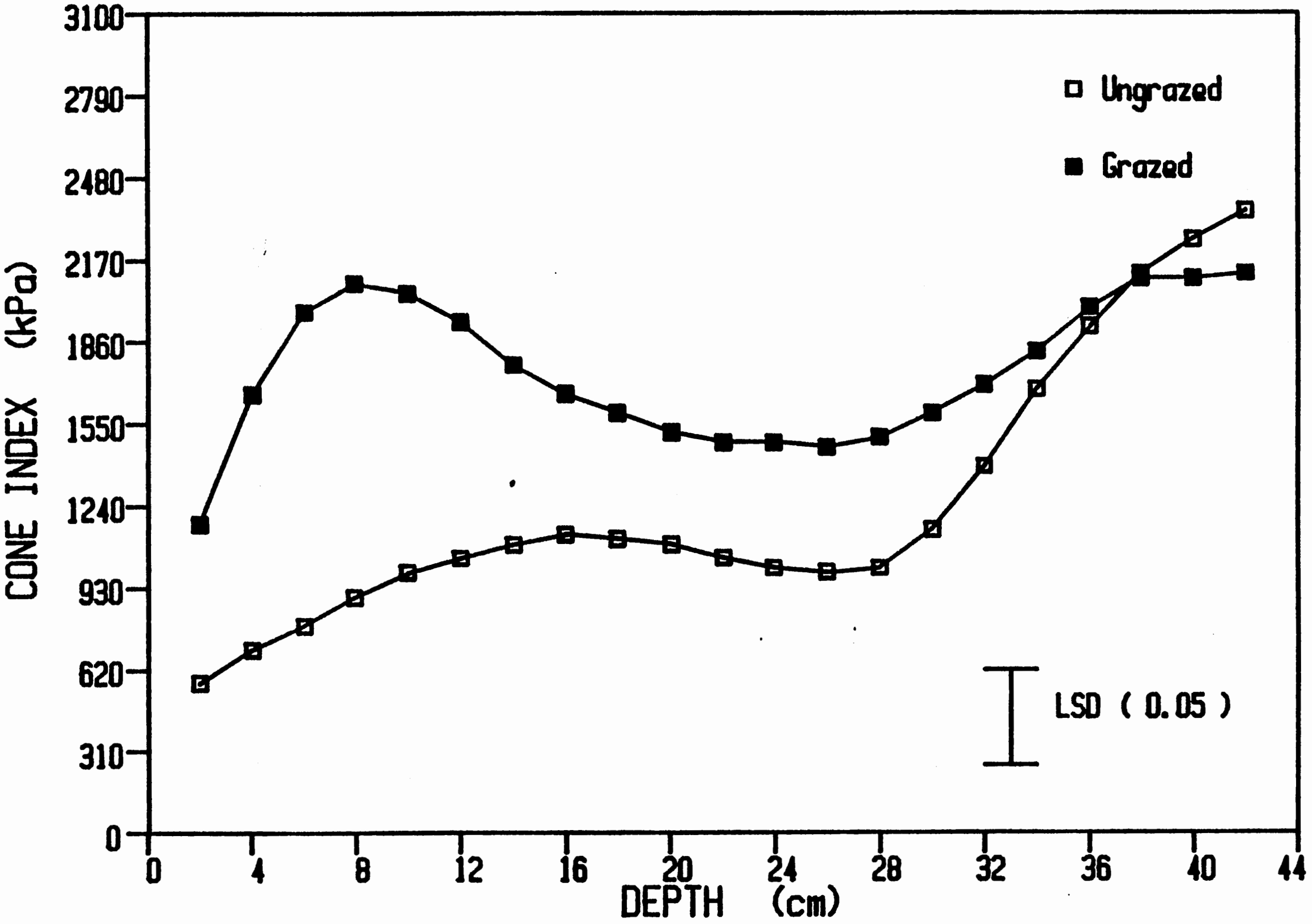

Figure 22. Soil strength for grazed and ungrazed areas at Perkins after grazing.

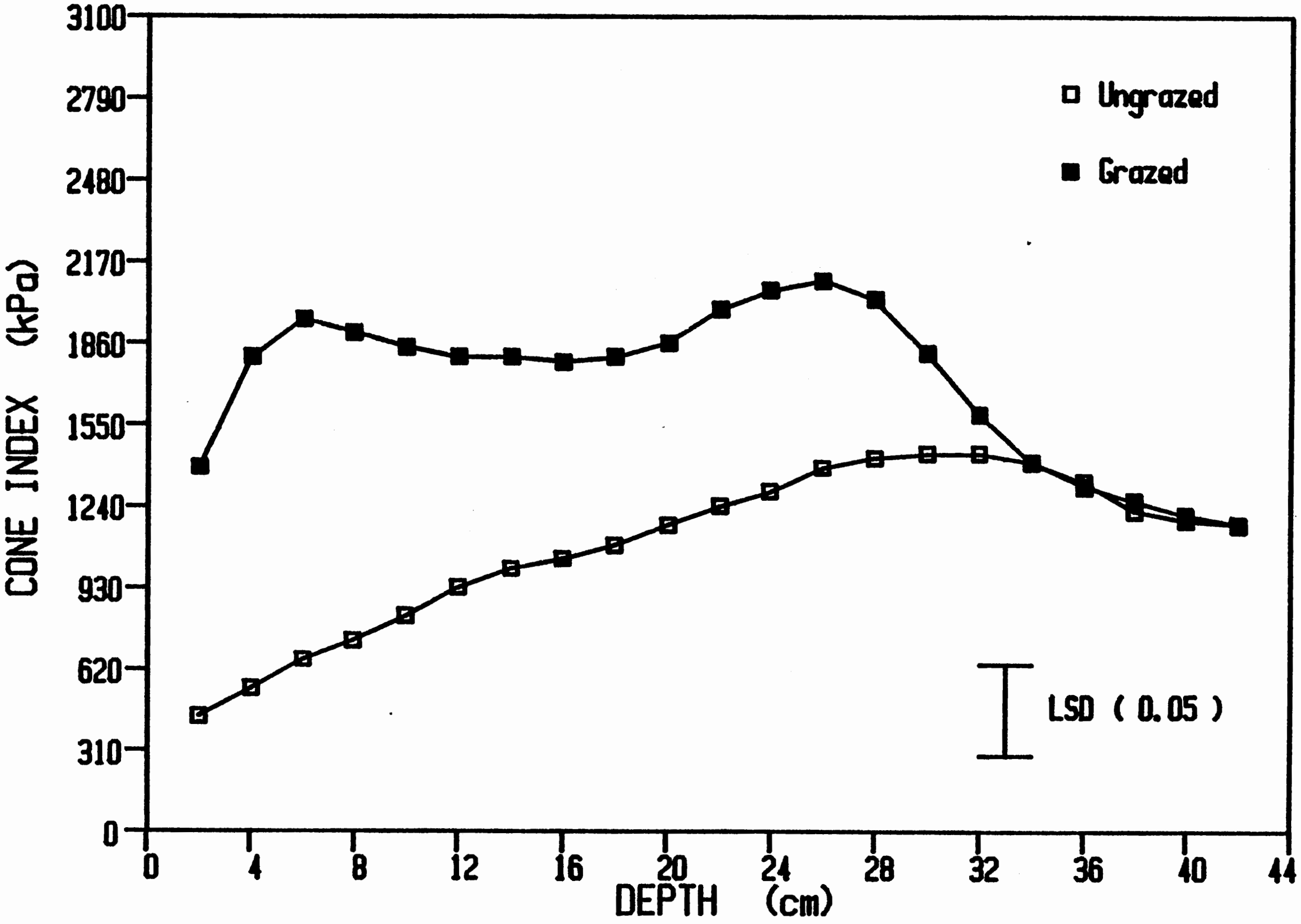

Figure 23. Soil strength for grazed and ungrazed areas at Lahoma after grazing.

VITA

CHAW FOH CHEE

Candidate for the Degree of

Master of Science

Thesis: EFFECTS OF ANIMAL TRAFFIC ON SOIL COMPACTION IN WHEAT PASTURES IN OKLAHOMA

Major field: Agronomy

Biographical:

Personal Data: Born in Labuan, Sabah, Malaysia, on June 26, 1962, the son of Mr. Chee Man and Mrs. Chock Sui Lan.

Education: Graduated from La Salle Secondary School, Kota Kinabalu, Sabah, in November, 1981; received Bachelor of Science Degree in Agronomy from Oklahoma State University in May 1986; completed requirements for the Master of Science Degree at Oklahoma State University in December, 1987.

Professional Experience: Part-time employee in the Department of Plant Pathology, Oklahoma State University, August, 1985 to August, 1986. Part-time employee in the Department of Agronomy, Oklahoma State University, September, 1986 to November, 1987.

Member: American Society of Agronomy; Crop Science Society of America; Soil Science Society of America; International Society of Soil Science