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EFFECT OF CROPPING SYSTEM ON SOIL STRUCTURE
AND GROWTH AND DEVELOPMENT OF SUGAR BEETS
(BETA VULGARIS, L.)

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EFFECT OF CROPPING SYSTEM ON SOIL STRUCTURE AND GROWTH AND DEVELOPMENT OF SUGAR BEETS (BETA VULGARIS, L.)

By

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ABSTRACT

EFFECT OF CROPPING SYSTEM ON SOIL STRUCTURE
AND GROWTH AND DEVELOPMENT OF SUGAR BEETS
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The effect of cropping system on the structure of a Charity clay soil was studied in 1982 and 1983 in an established experiment initiated in 1972 at the Saginaw Valley Bean and Beet Research Farm. Field studies were conducted for sugar beet growth and development to determine the influence of cropping system on the modification of soil structure.

The soil structure indices measured were bulk density, saturated hydraulic conductivity, total porosity, air porosity, mean-weight diameter of soil aggregates and their distribution at different size ranges. All the indices were affected by the soil depth within the plow depth (0 to 0.23 m). The magnitude of change was different among the sampling dates due to freezing and thawing, wetting and drying and/or the root system effects of sugar beets. A cropping system with 50% or more corn contained

high percent of aggregates with diameters between 5 to 0.5 mm. However, during the period of this study, the corn-beets system showed more dynamic changes in soil structure.

The positive linear correlation found between mean-weight diameter and soil organic carbon and the C/N ratio indicates the importance of the continuous additions of organic matter in modifying soil structure. Sugar beet growth and development were measured by leaf area index, taproot to leaf weight ratio and the fibrous root length density. The corn-beets system had lower leaf area index and taproot to leaf weight ratio and higher fibrous root length density than the corn-beans-beans-beets system. That could be the reason for the lower sugar beet yield in the corn-beets system where most of the assimilates were probably used by the fibrous roots.

The fibrous root length density was significantly correlated with the leaf area index and with the final crop yield at specific root sampling positions below the taproot. This will help locate the optimum sampling positions for root studies which will save time and energy and assist in the best placement of fertilizer.

DEDICATION

To my parents and grandfather

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Depending on the amount of crop residues produced, different cropping systems may benefit or deteriorate the soil structure. The depth to which soil structure is affected is very important for plant growth and development. The effect of different crops on soil structure with depth will be reflected by soil aeration, bulk density, water conductance and aggregate stability. Beneficial effects will result in water and nutrients being available to unimpeded roots which proliferate with minimum exerted pressures. Therefore, the maximum capacity for crop yields will not be restricted as far as soil structure is concerned.

For a given soil, many factors which act simultaneously are involved in the modification of soil structure. They include physical, chemical, biological and environmental factors which are integrated over time. The most important is the availability of organic matter upon which the magnitude of the other factors will depend. As the amount and characteristics of organic matter varies, the effect of microbial activities, freezing and thawing, and wetting and drying on soil structure will vary accordingly.

Soil compaction and wind and water erosion, which are the consequences of poor soil structure, will result in diminishing crop yields. To preserve the soil and increase its productivity, researchers have tried several techniques including different tillage practices and the addition of chemical conditioners. Good results have been obtained, but the applicability of these techniques are limited due to their high costs, especially in the developing countries.

A well known practice, which has been studied for many years, is the use of different cropping systems to maintain or improve soil structure and hence its productivity. Several observations have suggested that some plant species have greater ability than others to overcome mechanical stress in the soil. Plants which display this characteristic may improve soil conditions for crops which are planted subsequently. To what extent cropping systems can modify soil structure, especially at different depths, is not completely understood. Variations in soil types, the factors involved and the indices used are contributing components to be understood.

Cropping system effects in modifying soil structure with depth will be reflected upon root growth and development. Root distribution studies under field conditions as related to cropping systems and soil structure are limited, especially for root crops. Including root densities at different soil depths with the other indices will help in characterizing soil structural modifications by the different cropping systems.

With this background, the working hypothesis is that cropping systems have differential effects upon soil structural modification and root distribution with depth. Evaluating structural changes with soil and plant indices make yield correlation studies with these parameters more pronounced. The objectives of this study were:

1. To evaluate the effect of different cropping systems after 11 years on the following soil physical indices: a) saturated hydraulic conductivity, b) bulk density, c) total porosity, d) air porosity at 600 mm water tension and e) aggregate mean weight diameters and their stability.
2. To relate selected phenological measurements to the above indices.
3. To relate root growth measurements in the greenhouse to field measurements as they are affected by soil structure with depth.
4. To relate the measured soil physical indices to sugar beet yield.

LITERATURE REVIEW

I. Introduction

Soil structure controls many of the soil properties which have been studied extensively. In order to understand this phenomenon it is important to know what factors could affect its modification as reported in the literature.

The next three sections deal with the concept of soil structure where its definitions and its stabilization as affected by several factors will be explained. As far as the effect of different cropping systems on soil structure are concerned, their beneficial and deleterious effects will be reviewed in sections V and VI. The last section explains some ways of identifying good soil structure and how to maintain and/or improve it.

II. Soil Structure in the Field of Soil Science

Researchers have worked with soil structure for more than two centuries in order to understand and improve this phenomenon.

Unfavorable soil structure could limit the plant roots from reaching water and nutrients which otherwise could be beneficial to plant growth (Baver, Gardner and Gardner, 1972). From this prospective they suggested that soil structure should be considered as a parameter of soil fertility.

2.1. Soil Structure as a Physical Property

The soil physical conditions under which plants grow and develop are very important. For the scientific evaluation of various agricultural and reclamation practices, parameters describing these physical conditions must be estimated. Such estimates are particularly needed for direct regulation of physical properties during soil cultivation in intense agricultural systems.

The physical conditions for a given soil can be expressed by its structure. Marshall (1962) defined soil structure as the arrangement of the soil particles and the pore space between them. It includes the size, shape, and arrangement of the aggregates formed when primary particles are clustered together into large separable units.

2.2. Importance of Soil Structure

The general agreement in the literature is that good soil structure can improve, directly or indirectly, some physico-chemical properties of a soil. Page and Willard (1948) stated, "The future of agriculture on many of our soils depends largely on how well favorable soil structure can be maintained or increased". Structural improvement might influence soil-water relationships because aggregate stabilization promoted increased water infiltration (Jamison, 1953)

The dynamic changes in soil structure, due to the interrelated factors involved, make it difficult to define exactly what would be the optimum soil structure (Danilson, 1972). At the same time, well aggregated soils were found to exhibit increased infiltration, reduced erosion and runoff, increased seedling emergence, and would help to maintain a favorable soil-air-water regime for plant growth and microbial activities (Thien, 1976).

2.3. Some Indices for Soil Structural Studies

Since the soil matrix consists of solid, liquid and gaseous phases, their interaction is considered to be very important in describing the physical state of the soil profile. Nikolayev (1975) formulated three equations to be used as indices for each phase and a general equation for the interaction among the three phases. He suggested that using this kind of modulation would reflect the soil productivity conditions.

Leamer and Shaw (1941) reported that Schumacher recognized the importance of the distribution of pore size for plant growth as early as 1864. Schumacher introduced the terms "capillary" and "non-capillary" pore space to designate the small and large pore space, respectively. Russell (1971) used the term structural pores, which include coarse, medium and fine sizes. He stressed that the fundamental problems in soil structure management are concerned with the creation of these pores and their stabilization when formed.

In order to characterize the structural behavior of a soil, other indices have been used. They include bulk density, hydraulic conductivity, aggregate stability and soil strength. Even though correlations may not exist between all of these indices (Sorochkin, 1975 and Voznyuk, Kuzmich and Volkova, 1980), scientists have used one or several of them.

III. Stability of Soil Structure

From the stand point of plant growth and development, good soil structure is usually measured by the ability of the soil to form water-stable aggregates.

3.1. Definition of Soil Aggregates

A broad definition of soil aggregation which can be related to soil structure was given by Woodruff (1939). He defined it as "that physical property which affects the functional behavior of the soil with respect to water absorption, aeration and root penetration". A more precise definition of soil aggregates was given by Martin *et al.*, (1955). They defined a soil aggregate as "a naturally occurring cluster or group of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent aggregates".

3.2. Aggregate Formation and Stabilization

As mentioned previously, aggregate formation involves primarily the orientation of soil particles, and bringing them together closely so that when allowed to dry the physical forces hold them firmly (Baver, Gardner and Gardner, 1972) Chemical and electrical forces may also be involved in at least a minor way (Martin *et al*., 1955; Stefanson, 1968 and Greenland, 1971). Also, the size and stability of dry soil aggregates may be influenced by $CaCO_3$ and Al and Fe hydroxides (Siddoway, 1963 and Bond and Harris, 1964). Tisdall and Oades (1982) concluded that aggregates < 0.25 mm are stabilized by organo-mineral complexes and polysaccharides. Meanwhile, the stabilization of aggregates > 0.25 mm depend largely on the amount of roots and hyphae present in the soil.

3.2.1. Effect of Swelling and Shrinking Characteristics of Clay Minerals

The stability of soil aggregates will be influenced to a great extent by the swelling and shrinking ability of clay minerals. Mazurak (1950) predicted that the order of greater water-stability of any aggregate size would be smectite > hydrous mica > kaolinite. Soils containing smectite showed an almost reversible swelling and shrinking on rewetting and redrying. On the other hand, soils containing kaolinite or hydrous mica showed an initial large volume decrease on drying with only a limited swelling on rewetting (Yong and Warkentin, 1966). Uehara and Gillman (1981) found that the swelling ability of clays depend on their activity. An activity factor, which was defined as the ratio between plasticity index and percent clay-sized particles, was related to the surface area of the clay mineral.

3.2.2. The Role of Organic Matter

The significant role of organic matter in aggregate stabilization results from their reduction of swelling, reduction of destructive forces by entrapped air, decrease in wettability, and by their strengthening of the aggregates (Robinson and Page, 1950).

During the cultivation of arable lands, the organic matter between aggregates becomes more exposed to further decomposition by soil microorganisms which will reduce soil aggregation (Stoneman, 1973). Miller and Kemper (1962) found that incorporation of alfalfa into the soil affected aggregate stability only for a short period of time. Sufficient amounts of organic matter should therefore continuously be available. For unstable and poorly permeable soils, Williams and Cooke (1961) suggested that more organic matter might be needed than was given by the residues of arable crops grown.

3.2.3. The Role of Soil Microorganisms

Under suitable environmental conditions of nutrient and water availability, optimum soil temperature and pH, soil organisms efficiently breakdown fresh organic materials (Harris, Chesters and Allen, 1966). Further decomposition of the partially decomposed organic matter will result in more complex compounds such as fulvic and humic acids. Synthesis of these organic compounds requires the presence of some enzymes which can be produced by other microorganisms (Hamblin and Greenland, 1977). Filamentous microorganisms can directly stabilize soil aggregates. The adherence of soil particles to the mucilage which covers the hyphae was found to be an effective process in aggregate formation (Aspiras et al., 1971).

Some negative effects on soil structure by some microorganisms have been speculated. McCalla (1951) suggested that production of gases or highly hydrated organic materials might interfere with water movement in the soil as a result of decomposition and/or a change of aggregate stabilizing agents. Fahad et al., (1982) also related their low infiltration data after 6 years of soybeans to some microorganisms clogged the soil pores.

3.3. Mechanisms of Aggregate Stabilization

3.3.1. General

Several mechanisms have been proposed for the stabilization of soil aggregates. They include the linkage of clay particles by water-dipoles, cross-bridging and sharing of intercrystalline forces and interaction of exchangeable cations between oriented clay plates. The involvement of soil particles by precipitated and irreversibly dehydrated colloids such as silicates, sesquioxides and humates are also considered.

Aggregates may be stabilized against water entry by the presence of hydrophobic organic materials as fats and waxes. The interparticle linkage by organic polymers that form bonds through their functional groups with the surface of two or more clay particles is another important mechanism. A comprehensive review of the theories involved in aggregate formation and stabilization was given by Harris, Chesters and Allen (1966).

3.3.2. Clay-Organic Interactions

Clays were considered to associate in parallel alignments to form quasi-crystals or domains. Then these crystals were formed into micro-aggregates which were held together by organic polymers (Tabibudeen, 1981). Mortland (1970) concluded that the dominant factors determining the nature of clay-organic interactions are the properties of the organic molecule, the water content of the system, the nature of the exchangeable cation on the clay surface and the unique properties of the clay mineral structure.

Since clay particles are negatively charged, the adsorption mechanism of organic polymers will vary according to their electrical nature. For example, Van der Waals forces and hydrogen bonding are thought to be important mechanisms in the bonding of uncharged polysaccharides to clay particles (Clapp, 1972). The effect of these interactions depends mainly on the molecular weight of the polymer. As the molecular weight increases, the additive effect of the physical adsorption by Van der Waals force will be very significant.

Stability of soil aggregates by clay-organic interactions will be highly affected, among other factors, by the types of organic polymers and exchangeable cations in the soil. For example, humic and fulvic acids were found to be absorbed by clay minerals via ionic linkages with di-and tri-valent cations (Schnitzer, 1969; Greenland, 1971 and Theng, 1976). Meanwhile, adsorptions of polysaccharides was found to be primarily through physical forces, such as Van der Waals forces (Greenland, 1965 and Hamblin and Greenland, 1977). At high concentration of polycations, as is the case of Ca and Mg in calcareous soils, the strong aggregation may be explained by the strong bonding of the carbonyl group of polysaccharides to these cations (Clapp, 1972).

IV. Effects of Seasonal Variations on Soil Structure

Characterization of soil structure by aggregate formation and stabilization indicates that it is a complex and a dynamic process. The combination of the different factors involved and their changes over time influences the structural behavior of a given soil.

Aggregation is highly affected by the activity of soil microorganisms. At the same time, microbial activities are controlled by the soil's environment which in turn is closely related to seasonal variations. Wilson and Browning (1946) concluded that variations in the degree of aggregation should be expected between samples collected over a period of time. A definite seasonal trend on aggregate stability was found by Strickling (1950).

4.1. The Action of Freezing and Thawing

The effect of freezing and thawing appears to be one of the important factors on aggregate variations between seasons. Bisal and Nielsen (1967) indicated that the reduction in the percentage of erodible aggregates at high moisture content was due to freezing and thawing.

Depending on the aggregate sizes and their moisture content, soil structure can be highly affected by the processes of freezing and thawing. For example, Hinman and Bisal (1968) concluded that freezing and thawing and subsequent drying might increase or decrease the proportion of aggregates less than 0.1 mm in diameter. Also, Chepil (1953) found that the breakdown of aggregates greater than 0.84 mm during the winter was associated with an increase of water-stable aggregates less than 0.01 mm in diameter.

Other indices which may be related to soil structure also can be affected by freezing and thawing. Benoit (1973) found that freezing and thawing decreased the hydraulic conductivity at high soil moisture while increased it at low water content. Bolton, Dirks and Findlay (1979) related the variation in pore space observed between years to the level of winter freezing and to the moisture conditions in the spring.

4.2. The Action of Wetting and Drying

In conjunction with freezing and thawing, wetting and drying also have a large effect on soil aggregates. Water enters between aggregates at different rates depending on the pore-size distribution. The result will be an uneven degree of wetability among aggregates, hence the water will act unequally on the binding agents. Baver, Gardner and Gardner (1972) summarized the causes of crumb breakdown as a result of wetting:

1) dispersion of the cementing material

2) reduction in cohesion with increasing moisture content
3) compression of entrapped air and
4) stresses and strains set up by unequal swelling due to soil heterogeneity and non-uniform wetting.

Some of the above processes may be reversed upon drying resulting in a stabilization of soil aggregates. The significant effect of wetting and drying on soil structural modification will depend on soil type and its constituents, moisture of the aggregates at the time of wetting and the intensity of wetting.

Generally, it has been found that maximum aggregate stability occurs in the summer, followed by a gradual decline during the fall and early winter with an increase in the spring and early summer (Stefanson, 1968,1971). During the spring time the availability of organic matter and the favorable environmental conditions for microbial activities will result in an increased aggregate stability. During the fall and winter months the soil will be more exposed to weather changes. For example, the effect of intensive rain on poorly structured dry soil may result in unfavorable soil conditions for the next growing season.

V. The Impacts of Cropping Systems and Rotational Lengths on Soil Structure

Different agricultural crops have different rooting patterns and produce different amounts of biomass. Therefore, it will be expected that similar crops may have specific impacts on soil structural modifications. From these perspectives, different cropping systems have been studied extensively to find answers for increasing soil productivity.

With the increasing demand for food production, scientists considered soil structural improvement as one of the achievable approaches. Concerns about the possibility of modifying soil structure by different cropping systems have led researchers to study this phenomenon on already existing experiments. In making conclusions from such studies, we have to keep in mind the interrelationships among all factors involved.

5.1. Cropping Systems Effect

Modifications in the soil productivity have been observed by the use of different crops and cultural practices. Baver (1949) made an excellent review for the relations between some soil physical changes and crop production. He stated "There are numerous studies in the literature showing the effect of certain cropping and soil management practices upon the changes in the physical properties of the soil. These studies provide evidence of the beneficial or detrimental effects of a given practice upon the soil. From such results, one can deduce what will probably happen to crop yields".

Data available in the literature indicate the significance of some agricultural practices, including cropping systems, on soil structure modifications. Cary and Hayden (1974), meanwhile, indicated on a silt loam soil that cropping history did not show any effect on either pore-size distribution or on the soil hardness.

The divergent results reported in the literature concerning the effect of crop rotation on soil structure can be attributed to several reasons. Most importantly, methods of manipulating the soil under which the experiments were run could lead to different results. The lack of consistency in the cultural practices and in the methods of soil sampling and analyses may also lead to some conflicting results.

5.1.1. Beneficial Effects

Generally, a cropping system which includes plants with massive and extensive root systems and good vegetative cover may be beneficial to soil structure (Harris, Chesters and Allen, 1966; Ojeniyi and Dexter, 1979 and Tisdall and Oades, 1980). The beneficial effects from these crops may be due to the action of their roots and from providing enough organic matter to the soil.

The presence of extensive root system plants in the soil can stabilize the aggregates in several ways. First, during plant growth, the roots can stabilize the aggregates physically and chemically. Adherence of fine soil particles to living root hairs and production of organic complexes constitute the major mechanisms. Second, when plant roots die, they become an additional source of organic matter in the soil (Allison, 1973). Greenland, Lindstrom and Quirk (1962) found small reduction in aggregate stability of Red Brown soils which was in pasture for many years.

It seems that good soil structure can be restored either by permanent grasses or by the inclusion of some beneficial crops in a rotational system. For example, Low (1955) reported that periods between 5 and 50 years, depending on the soil texture, were required to restore the stability of old arable soils to levels comparable to those under permanent grass. Also, Grieve (1980) found a significant reduction in aggregate stability after only 2 or 3 years the soil was out of grass.

Winter wheat has been found to stabilize larger aggregates more than sorghum or soybean (Armbrust _et al._, 1982). However, Siddoway (1963) showed that inclusion of grasses and legumes in rotation with winter wheat and fallow resulted in lower stabilization of larger aggregates than under the more common wheat-fallow rotation.

Beneficial crops can provide part of the nutrients required by soil organisms as well as their physical and chemical functions in stabilizing the aggregates. Close growing crops with deep and well developed root systems, such as alfalfa, might increase soil porosity and permeability (Uhland, 1949). Van Bavel and Schaller (1950) found that aggregation was approximately twice as high under corn of corn-oats-meadow rotation as under continuous corn.

5.1.2. Deleterious Effects

In planning long term cropping systems we have to realize that some crops if planted continuously may not preserve the structural stability of soils. For example, Browning, Russell and Johnston (1942); Browning (1945); Strickling (1950) and Fahad et al. (1982) indicated that corn and soybeans had the same negative effect on building stable soil structures. Also, Armbrust et al. (1982) found that aggregate stabilities from soybean plots were lower than those from either grain sorghum or winter wheat plots.

It is apparent that corn and soybeans and probably other crops having similar growth habits and residue return lack the characteristics of the beneficial crops in stabilizing soil structure. Therefore, a rotation system which includes both kinds of crops may preserve the good soil physical conditions. Robertson (1955) found that cash crop rotations which did not have nitrogen supplying legumes resulted in poor soil structure while inclusion of green manure crops in the rotations improved those soils. Also, Asrar (1978) indicated that on a Charity clay soil the structure improved only in alfalfa-bean rotation. In other rotations, where alfalfa was not included, he found that in order to improve the soil structure, organic residues must be applied to the soil.

5.2. Effect of Length of the Rotations

Longer rotations which included legumes were found to maintain or improve soil structure (Newton and Drover, 1956). Also, Toogood and Lynch (1959) showed that a rotation of grains and legumes which lasted for 5 years had almost double the mean-weight diameter of soil aggregates than a wheat-fallow sequence. Bolton, Dirks and Findlay (1979) found, on a Brookston clay soil, that a 4 year rotation with 2 years of alfalfa had more total pore space than rotations with only one year of alfalfa.

Studies have been done to measure the length of time required for grass to produce adequate aggregation under certain soils. Low (1955) found that structure restoration of a clay loam soil took place rapidly in 2 to 4 years, with a gradual decreasing improvement in a parabolic manner up to 100 years. In a coarse textured soil Barber (1959) showed that aggregation increased linearly when measured in grass plots for 4 years. When grasses were involved in long term rotations (20 years) the geometric mean diameter of water-stable aggregates, hydraulic conductivity and air permeability increased curvilinearly with the age of grass (Mazurak and Raming, 1962).

VI. Effect of Soil Structure on Root Growth and Crop Yield

Soil physical properties generally deteriorate if the soil is intensively cultivated (Skidmore, Carstenson and Banbury, 1975). This deterioration will be followed by reductions in the soil productivity and hence crop production will be affected. Low (1973) concluded from a long term yield experiment (100 years) that changes in the state of soil structure over the years resulted in crop yield differences.

6.1. Effect on Root Growth

The amounts of water and nutrients absorbed by the plant root systems are highly influenced by the soil physical conditions. The effects could be through those properties which govern the soil's ability to retain and conduct water and nutrients or through the effects on root growth and functions (Eavis and Rayne, 1969). Greacen, Barley and Farrell (1963) reported a wide range of soil physical conditions that caused cessation of root elongation depending on texture, bulk density, soil water suction and plant species.

Even though soil bulk density may not be a good indication of soil permeability (Mason, Lutz and Peterson, 1957), it has been found that this parameter proved to be a good index of soil compaction. The ability of plant roots to penetrate different soil layers depend on the degree of compaction and on plant species. Bertrand and Kohnke (1957) found that corn roots did not penetrate a subsoil compacted to a bulk density of 1.5 Mg m^{-3}. When the bulk density was reduced to 1.2 Mg m^{-3}, the roots grew profusely. Barley roots were found to penetrate aggregates with bulk densities of 1.4 Mg m^{-3} but were restricted to the priphery at bulk densities of 1.8 Mg m^{-3} (Voorhees _et al._, 1971).

In order for plant roots to function properly they require soil pores larger than their diameters (Russell, 1977). At the same time, the volume and geometric arrangements of voids in the solid matrix of the soil will affect gaseous and liquid diffusion (Baver, Gardner and Gardner, 1972). But, positive effects of soil aeration on root growth will occur only if the roots are able to penetrate the soil. Tackett and Pearson (1964) found that at low bulk densities the elongation rate of cotton roots decreased as CO_2 concentrations increased to 24% even though O_2 concentration was 21%. At high bulk densities, CO_2 concentration did not affect root elongation rate. They suggested that soil strength was the limiting factor in the elongation rate. Gooderham (1977) related the decreased elongation rate of pea seedling roots in compacted soils to the lack of some growth regulating chemical compounds produced by the roots. When he added the growth active compound 3,5-diiodo-4-hydroxybenzoic acid to the soil the root elongation rate increased by up to 25%.

It is apparent that soils must be friable and well aerated, especially for root crops. Baver and Fransworth (1940) found that sugar beet yield decreased by about 4.5 to 9 Mg ha^{-1} when the soil air porosity was about 2% (v/v). They concluded that maximum beneficial effects of fertilizers could not be expected unless the soil structure was improved to permit adequate aeration for the growing beet. When the soil porosity increased by planting sugar beets on ridges the yield increased from 3.4 Mg ha^{-1} to more than 26.9 Mg ha^{-1} (Baver, 1949).

Evidence for the importance of soil aeration for sugar beet root proliferation was provided by Wiersman and Mortland (1953). They supplied the beets with a source of oxygen by mixing Ca-peroxide with the soil and found increased root length of the beets.

6.2. Effect on Crop Yield

The ultimate effect of the factors which affect shoot and root growth will finally appear on the crop yield. If we assume a crop has an optimum leaf area index (LAI), and can utilize the solar radiation efficiently (Shih and Gascho, 1980 and Mengel and Kirkley, 1982), then what factors may control its yield? As far as the soil is concerned, all the factors which are involved in its productivity will have some influence. Therefore, improvement in the soil's physico-chemical properties associated with crop rotation and proper soil management may also improve yields. Schuurman (1965) concluded that the beneficial effect of improved soil productivity on root growth will enhance the development of the whole plant.

In making yield correlations with soil structure, other growth controlling factors should also be considered. DeBoodt, DeLeenheer and Kirkham (1961) suggested that correlations between yield and soil structure often depend on the weather. Also, Low (1973) found correlation between the yields of cereals, peas and red beets with the stability of soil structure. But those correlations were based on the condition that the quantity of soil nutrients or disease was not a limiting factor.

Aggregate sizes and their stability as related to different crop rotations have been used for yield correlation studies. In a corn-oats-meadow rotation, corn yield was highly correlated with aggregation when expressed by mean weight diameter (Van Bavel and Schaller, 1950). Odland, Bell and Smith (1950) found the yields of onions grown in rotation with mangels, buck wheat, corn and red top were directly correlated with the amount of water-stable aggregates. On a silt loam soil, Salomon (1962) concluded that increased potato yields were due to improved soil aggregation rather than to other factors associated with organic matter.

Beneficial effects of soil structure modifications could result in improvements of soil fertility and tilth (Black, 1973). Therefore, in studying yield responses to soil and crop managements, crop yields can be related either to the physical or the fertility soil parameters or both. For example, in an experiment under different fertility levels and crop rotations, Bolton, Dirks and Aylesworth (1976) found that differences in corn yield were due to addition of N via a legume crop. On the other hand, Dirks and Bolton (1980) found that corn yield decreased in continuous corn plots. They related that to increased soil compaction which reduced nutrient and water availability as well as restriction of root growth.

VII. Improvements of Soil Structure

Variations in bulk densities within the soil profile may limit the vertical and horizontal distribution of plant roots. Therefore, knowing these restrictions may provide clues for the need of profile modifications. This knowledge can also lead to development of the most effective placement of fertilizers in the soil (Mengele and Barber, 1974 and Chaudhory and Prihar, 1974).

To insure good seed germination, root growth and crop yield the soil should be in suitable and stable physical conditions, provided other growth factors are not limited. Hagin (1952) found that larger aggregates promoted higher yields in a greenhouse experiment. Kuznectsova (1980) indicated that the plow layer would have a stable make up if aggregates >0.25 mm had a stability of 40% or more. Although these findings stress the importance of soil aggregation, the dependence of plant performance on a single-sized aggregates is doubtful. Instead, a mixture of granules of varying sizes showed the best effects on plant stand (Baver, Gardner and Gardner, 1972).

In fields typically planted for row crops, Hillel (1982) indicated that at least two zones should be considered in a soil structure management. First, a planting zone where the structure should be favorable for seed germination and seedling establishment would be needed. Second, a management zone in the interrow areas where soil structure should be coarse and open for water and air economy of the growing crop.

The complexity of the soil system and the different factors involved make it difficult to rely upon a specific procedure to maintain and/or improve soil structure. For example, a wide range of aggregate sizes and spatial arrangements (depending on soil texture and water content) can be obtained in a seedbed as a result of various tillage operations (Allmaras et al., 1965). Also, Henderson and Haise (1967) suggested the use of soil ammendments using appropriate tillage and crop sequences or sometimes adding organic manures.

Recently, various synthetic chemical conditioners have been proposed. Some improvements in soil physical conditions have been established by the use of polyvinylalcohol (PVA), polyvinylacetate (PVAc), dimethylaminoethylmetocrylate (DAEMA) and polyacrylamide (PAM) (DeBoodt, 1972). Meanwhile, McGuire, Carrow and Troll (1973) added (PVA) and (PAM) to a compacted sandy soil in greenhouse and field experiments and did not find any beneficial effects in the soil physical conditions.

Restriction of these conditioners to certain soil types, skills required for their applications and their high costs limited their use.

Throughout this review evidence has been presented for the beneficial and deleterious effects of certain cropping systems on soil structure. In order to assess these effects, Gerard, Sexton and Shaw (1982) suggested the use of periodic evaluation of mechanical impedance. We chose the use of both soil and plant indices to express the magnitude and dynamic changes of soil structure and to explain in more details the role of a specific cropping system.

MATERIALS AND METHODS

I. Description of the Experimental Area

The research area in which this study was conducted is located in the center of Saginaw County in Swan Creek Township (Section 9, T11N, R3E), at the corner of Swan Creek and Thomas Roads. Saginaw County is in the east-central part of Michigan, a few miles south of Saginaw Bay.

The county is part of the Saginaw lowland, a smooth low-lying plain which represents the old beds of glacial lakes preceding the present lake Huron. The surface geological formations were laid down by ice and water during the Wisconsin stage of the glacial period and subsequently were smoothed over by waves of glacial lakes and by shallow Lacustrine deposits.

The predominant soils of the county have fine textures and slow drainage and are adversely affected by too much rain in the spring which may reduce crop production (Moon, 1938).

1.1. General Properties of the Soil

The soil type of the experimental area was a Charity clay (Aeric Haplaquept; fine, illitic (calcareous) mesic). Particle size analysis indicated that this soil contained;

6.4% sand, 39.8% silt and 53.8% clay (Asrar, 1978). The clay fraction is dominated by vermiculite while smectite, chlorite, hydrous micas and quartz were presented in smaller amounts (Zielke, 1983).

The Charity series consists of naturally poorly drained soils developed in highly calcareous stratified lacustrine clay and silty clay materials (soil management group 1c-c).

As far as agricultural crops are concerned, these soils have certain limitations. These include moderate to high water table where artificial drainage is needed for good crop production. The soils have low permeability, have a poor workability when wet and poor bearing capacity for farm machinery during wet periods. Also, they are commonly deficient in Mn and/or Zn for susceptible crops (Mahjoory and Whiteside, 1976). The general research area showed the following soil test results; pH, 7.7; Bray P1 phosphorous, 17 mg kg^{-1}; exchangeable K, 226 mg kg^{-1}; exchangeable Ca, 5030 mg kg^{-1}; exchangeable Mg, 827 mg kg^{-1} and organic matter, 43g kg^{-1} [1/].

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[1] See MSU, Department of Crop and Soil Science mimeo of Saginaw Valley Bean-Beet Research Farm and Related Bean-Beet Research, 1983 Research Report.

1.2. Climatological Aspects

The common features of the climate of Saginaw county are long cold winters, mild pleasant summers, well distributed moderate precipitation and little wind. Generally, the climatic conditions are about the same for all parts of the county, as local variations in elevations are negligible (Moon, 1938).

The air temperature is somewhat modified because of the proximity to Lake Huron. The difference between the winter and summer mean temperatures is about 8° C. For the research area, maximum and minimum temperatures were measured each month during the period of study (1982-1983) are summarized in Table 1. The average frost-free season is 157 days from May 3 to October 7 which is an ample period for the growth and maturity of many crop species (Moon, 1938).

Rainfall is almost evenly distributed throughout the growing season and is normally sufficient for good crop production. However, due to the nature of the soils, short drought periods would result in reduction of crop yield (Moon, 1938). Monthly precipitation for the years 1982 and 1983 are shown in Table 2. As a result of the generally low wind velocities and high relative humidity, evaporation is moderately low. Of the possible amount of sunshine, 65 to 70% is the range expected during summers and only about 25% during winters (Moon, 1938).

Table 1. Monthly maximum and minumum air temperatures one meter from soil surface at the Saginaw Valley Bean-Beet Research Farm during 1982 and 1983.

Month	1982		1983	
	Maximum	Minimum	Maximum	Minimum
	°C			
January	7	-27	7	-17
February	7	-24	15	-17
March	15	-22	19	-19
April	24	-13	25	-6
May	23	-1	26	-3
June	29	4	36	3
July	33	8	34	6
August	30	0	34	8
September	31	0	33	-1
October	29	-6	28	4
November	19	-9	18	-9
December	18	-16	4	-22

Table 2. Monthly precipitation as measured by the US Weather Bureau Rain Gauge at the Saginaw Valley Bean-Beet Research Farm during 1982 and 1983.

	Precipitation	
Month	1982	1983
	mm	
January	60	23
February	12	23
March	25	84
April	32	116
May	84	156
June	78	90
July	67	49
August	65	64
September	77	130
October	19	75
November	102	78
December	83	51

II. Field Experiment

Field plots for this study were part of a larger cropping systems experiment initiated in 1972 at the Saginaw valley Bean-Beet Research Farm.

The cropping systems were selected to study their differential effects upon soil structural modification and its relation to sugar beet yield. The choice of sugar beets as the indicator crop was based on its sensitivity to changes in the soil physical conditions.

The experiment was arranged as a randomized complete block design with six cropping systems and four replications giving a total of 24 experimental units. Each unit was 20.1 m long and 5.7 m wide making an area of 1.15×10^{-2} ha. As far as tillage is concerned, the units received the same practices every year since 1972. The methods involved fall plowing with a mold board plow to a depth of 0.2 to 0.25 m, where the soil would be exposed to weather variabilities. In the spring prior to planting, the soil was harrowed once with a spring and a spike tooth harrow combination.

The cropping systems used involved combinations of the following crops; corn (Zea mays L.), oats (Avena sativa L.), alfalfa (Medicago sativa L.), navy beans (Phaseolus vulgaris L.) and sugar beets (Beta vulgaris L.). This study involved the following cropping systems; (1) corn-beets (C-B), (2) beans-beets (Be-B), (3) oats-beans-beets (O-Be-B),

(4) corn-corn-corn-beets (C-C-C-B), (5) corn-beans-beans-beets (C-Be-Be-B), and (6) oats-alfalfa-beans-beets (O-A-Be-B).

The entire experimental area received an application of 130 kg P_2O_5 ha^{-1} prior to planting in 1972. Thereafter, fertilizers were added based on the crop grown and the soil test level. During the growing season of 1983 all the experimental units under study were planted with sugar beets. Fertilizers applied in a band below and to the side of the seed composed of 336 kg ha^{-1} of 11-53-0 plus 1% B and 3% Mn, no K was added due to its high soil level (532 kg ha^{-1}). Nitrogen rates were 56 kg ha^{-1} for each cropping system plus an additional amount of 28 kg ha^{-1} was added to the beans-beets system. Additional N was broadcast as required in May.

Sugar beets (variety US H20) were planted on May 11 at a row spacing of 0.71 m and were thinned to 0.2 m between plants about five weeks after planting. Preemergence application of 6.7 kg ha^{-1} trichloro-acetic acid (TCA) and 4.5 kg ha^{-1} 5-amino-4-chloro-2-phenyl-3(2H)-pyridazmone (pyramin) were used to control weeds.

III. Methods of Soil Sampling

3.1. Undisturbed Core Samples

Undisturbed soil samples were taken to characterize the field soil physical conditions as they were affected by the different cropping systems. The soil cores were sampled by a double cylinder hammer driven core sampler described by Jamison, Weaver and Reed (1950). The inner aluminum cylinder which contained the sample had an inside diameter of 76 mm and a length of 76 mm.

Cores were taken from positions in each plot as to avoid tractor tracks and other obviously compacted areas. During the fall of 1982 and spring of 1983 samples were taken from all the experimental units (plots). During the fall of 1983 only corn-beets, oats-beans-beets and corn-beans-beans-beets systems were sampled. For each sampling date five subsamples per plot were taken at 0.0 to 0.08 m, 0.08 to 0.15 m, 0.15 to 0.23 m and 0.23 to 0.31 m soil depths. Therefore, with the cropping systems used and their four replications, 480 soil cores were sampled in 1982 and the same number was taken during the spring of 1983. In the fall of 1983 one-half of the cropping systems were sampled giving a total of 240 cores. Excess soil over the cylinder edges were trimmed off with a sharp knife and the core samples were put in paraffin-coated 0.473×10^{-3} m^3 sized ice cream containers which were labelled and sealed. The samples were stored in a cooler at 4° C for laboratory analysis.

3.2. Disturbed Soil Samples

For aggregate analyses, disturbed soil samples were taken at two sampling dates. During the fall of 1982 samples from all the experimental units and from uncultivated area (virgin soil) located at the south end of the Research Farm were taken while during the fall of 1983 only the corn-beets, oats-beans-beets and corn-beans-beans-beets systems were used for sampling.

A composite sample from 0.0 to 0.1 m and 0.1 to 0.2 m depths was taken from each experimental unit and the uncultivated area. Each composite sample consisted of 24 probes taken at random following a zigzag pattern across the plot, mixed in a plastic pail and passed gently through a 5 mm screen while moist. Screened samples were air-dried and sealed in labelled plastic bags until laboratory measurements could be conducted.

IV. Soil Measurements

4.1. Undisturbed Samples

Indices used in this study to evaluate field soil structure included saturated hydraulic conductivity (SHC), air porosity at 600 mm water tension (AP), total porosity

(TP) and bulk density (BD). All the indices were measured in the laboratory on the same soil core for each subsample.

Soil core preparation included covering the bottom with a Whatman filter paper number 2 and a piece of cheesecloth and secured with a rubber band. A 25 mm deep plastic ring having the same inside diameter as the aluminum cylinder was fastened to the top of the cylinder with masking tape.

The prepared cores were placed in a large aluminum pan containing tap water for 24 to 48 hours for saturation by capillarity. Saturated cores were weighed carefully to avoid water losses.

Saturated hydraulic conductivity (SHC) was measured by the constant head method (Klute, 1965). A time of 60 minutes was used for the determination.

At the termination of SHC experiment, the cores were allowed to drain for about 2 minutes before they were put on a tension table described by Leamer and Shaw (1941) and modified by Vomocil (1965). The samples were allowed to equilibrate with 600 mm water column for 24 to 48 hours. After equilibrium was reached, air porosity (AP) of each sample was determined by the method of Vomocil (1965) using an air-pycnometer system. Bulk densities were measured by the method of Blake (1965).

Using an average value of 2.65 kg m^{-3} for soil particle density, total porosities were determined by the procedure of Vomocil (1965).

4.2. Disturbed Samples

For each sampling date, duplicate subsamples were used for aggregate analysis by the wet-sieving method of Kemper and Chepil (1965) with some modifications.

Six sieves each with a diameter of 250 mm and a depth of 45 mm and had openings of 4, 2, 1, 0.5, 0.25 and 0.106 mm were assembled in order of size (coarsest sieve on top). The set of sieves was locked in a Yoder (1936) type of sieving machine, immersed in water and oscillated for 2 minutes to remove trapped air before soil was added. (The machine had a stroke length of 38 mm and a speed of 30 oscillations per minute).

An air-dried subsample (50 g) with predetermined moisture (w/w) was placed on the top sieve when the machine was at its highest position. The soil was allowed to wet by capillarity for 10 minutes and then sieved for 30 minutes. Aggregates retained in each sieve were washed in 500 ml beakers, dried at 105^{o} C for 24 hours for oven dry weight. The oven-dry aggregates were placed in a baffled mixer cup, 10 ml of sodium hexametaphosphate (5 g L^{-1}) Kemper (1965), 350 ml of water were added and the mixture was mixed with a mechanical stirrer for 5 minutes. (The stirrer is popularly referred to as a milk shake mixer). Sand was removed from the dispersed soil by wet sieving on the Yoder machine, collected from the screens and the dry weight was determined.

True aggregate weights were determined by subtracting the amount of sand retained on each sieve from the corresponding aggregate-size weight.

Fraction weights of true aggregates were corrected for moisture content and used for calculations of aggregate stability (Kemper, 1965) and mean-weight diameter (MWD) (Van Bavel, 1949 and Youker and McGuiness, 1957).

V. Methods of Plant Sampling and Measurements

5.1. Leaf Blades and Taproots

In order to relate crop responses to soil structural modifications, sugar beet leaf blades and their taproots were sampled during the growing season of 1983.

Leaf area was determined on leaf blades removed from 3 areas (0.71 x 0.86 m) within each plot. All blades were removed and area was determined by a Lambda leaf area meter, Model LI-3050 A. Based on the section area for leaf samplings and an average leaf areas per section per plot, leaf area index (LAI) was calculated (Leopold, 1975).

Taproots were sampled on July 25, August 17, and 26, September 13 and October 9. Ten plants per plot were chosen randomly and were dug out by hand. Discarding the petioles, taproots and leaf blades were separated and were put in separate marked plastic bags for further processing.

Measurements of taproot-leaf weight ratio (TLWR) were based on both fresh and dry weights of leaf blades and taproots. Leaf blades of the 10 plants sampled for each plot were weighed fresh, dried at 60°C for 48 hours and reweighed. The taproots were cleaned from soil, weighed, sliced longitudinally to thin sections, dried at 60°C for 48 hours and reweighed. An average weight of 10 plants per plot was used to calculate TLWR (Snyder *et al.*, 1979).

5.2. Fibrous Root Systems

To investigate the relationships between sugar beet root distribution and soil structure at different depths, soil-root cores were sampled at the end of the 1983 growing season.

Soil-root cores of one plant per plot were sampled on October 10 from the C-B, O-Be-B and C-Be-Be-B cropping systems by a mechanical soil-root sampler (Strivastava, Smucker and McBurney, 1982).

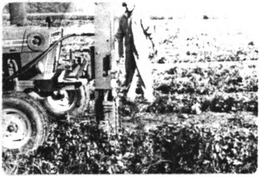
The following technique was followed so that the majority of the roots would be included in the samples. Two opposite beets which had about the same size were pulled from adjacent rows and their central positions were marked with flags. The soil between the marked positions (between the rows) was removed to a depth of 0.23 m. This allowed the soil-root cores to be sampled between a depth of 0.23 and 0.69 m.

Figure 1 shows the procedure that was used to remove the cores from the soil. Picture A shows the core being driven into the soil. When the desired depth was obtained, the core was removed utilizing a puller mounted on the tractor (Picture B). This yielded a soil-root core 0.23 x 0.46 m. After removal from the plot, the large core was fractionated into 18 subsamples each measuring 0.08 m on a side (Picture C).

Since the rows were 0.71 m apart and the cores were 0.23 m wide, three contiguous cores were taken to sample the entire root volume between the rows. The subsamples above were then stored for bulk density, moisture content and root length measurements.

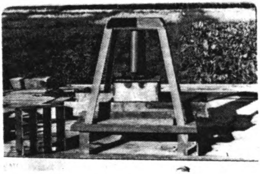
5.3. Sugar beet Yield and Quality

Yield measurements were determined by machine harvesting 40.2 m of row, weighing the beets and then calculating the yields on a fresh weight basis. A subsample of 10 beets per plot were taken for quality analysis. Percent sugar and clear juice purity were determined by the



A

B



C

Figure 1. Processes for taking the soil-root core samples. A, driving the core sampler into the soil. B, the core pulling frame mounted on the tractor. C, the core being subsectioned by a 9-cell fractionator.

Michigan Sugar Company quality Laboratory according to the procedure described by Dexter, Frakes and Snyder (1967).

VI. Greenhouse Experiment

A greenhouse experiment was conducted to relate root growth as affected by variations in soil structure with depth to those measured in the field.

6.1. Soil Sampling and Preparation

Duplicate soil cores from each plot were taken at depths of 0 to 0.08 m, 0.08 to 0.15 m, 0.15 to 0.23 m and 0.23 to 0.31 m during the fall of 1983 giving a total of 192 soil cores. The methods of sampling were the same as for the field undisturbed core samples.

Oven dry weight and bulk density of each subsample were determined. The moist weight of each core was determined. A small soil sample (about 10 g) was taken from the bottom, oven dried at 105^{o}C for 24 hours and its moisture content was determined gravimetrically. Oven dry weight and bulk density of the soil core were calculated by the following equations:

$$\text{oven-dry weight} = \frac{\text{moist weight of the soil core}}{1 + \frac{\text{sample moisture \% (w/w)}}{100}}$$

and

$$\text{bulk-density} = \frac{\text{oven dry weight}}{\text{bulk soil volume}} \qquad \text{where}$$

bulk soil volume = volume of the aluminum cylinder

$= 0.345 \times 10^{-5}\ m^3$.

Plants were grown in containers similar to the soil core seedling test described by Asady, Smucker and Adams (1985). The soil in the cores was brought to 80% (w/w) of field capacity, five navy bean seeds (seafarer) were pressed into the soil and then the seeds were covered with 130 g of quartz sand. The core was then placed into a carton containing quartz sand (Figure 2). Moisture was maintained at 80% field capacity throughout the growth period. After planting the sand covering the seeds was moistened to aid germination.

After germination the stands were thinned to one plant per core. Nutrients were added in solution after thinning to give 20 mg N kg^{-1}, 40 mg P kg^{-1}, 20 mg Mn kg^{-1} and 5 mg Zn kg^{-1}. Sources used were $NH_4H_2PO_4$, $MnSO_4 \cdot H_2O$ and $ZnSO_4 \cdot 7H_2O$, respectively.

The experimental units were arranged as a randomized complete block design with 4 replications.

The light sources were high pressure sodium lamps which gave an average irradiance of 76 W m^{-2}, and were

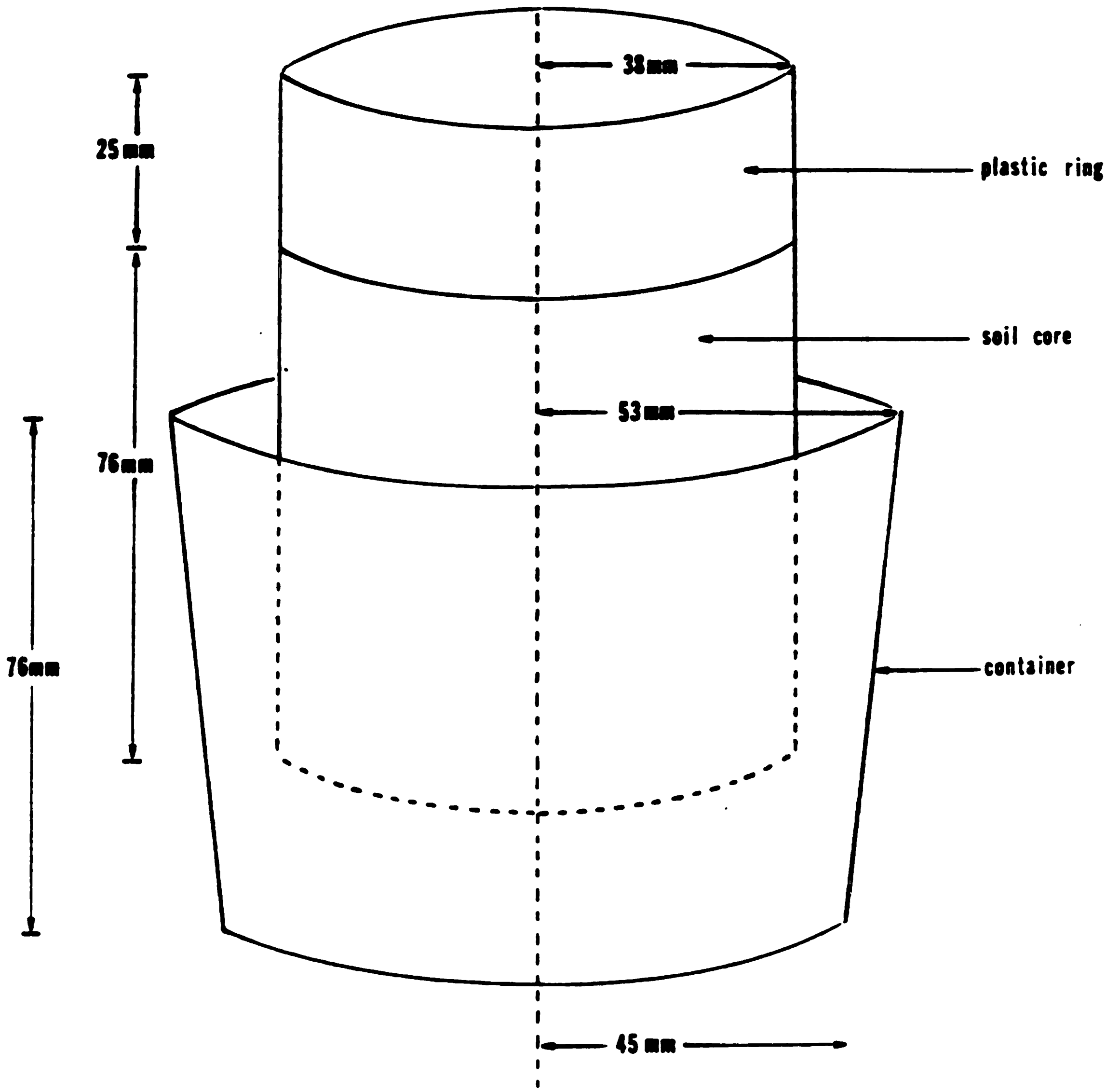


Figure 2. An assembly of a soil core with its plastic ring and their dimensions for the greenhouse experiment.

automatically controlled to give a photoperiod of 16 hours per day. During the day temperature was between 20 and 28°C while night time temperature was constant at 20°C.

6.2. Harvesting and Root Sampling

Plant shoots were harvested 26 days after planting, dried at 60°C and the dry weight was determined.

The harvested soil cores were subsampled by removing a core 48 mm in diameter by 76 mm in length from the center of the larger core. This was done so as to eliminate measuring roots which would grow between the cylinder and the soil core (Asady, Smucker and Adams, 1985). The diagram in Figure 3 shows the thin walled sampling tube and the plunger for removing the core from the sampling tube. The sampling core was pressed into the larger core using a manually operated hydraulic compressor. The samples were stored in a cooler at 4°C until further processing.

VII. Separation of Roots and Their Length Measurements

Fibrous roots from the field and greenhouse samples were separated from the soil by washing in a hydropneumatic elutriation system (Smucker, McBurney and Strivastava, 1982). A soil-root core was broken by hand to about 20 mm diameter pieces and soaked in a saturated sodium hexametaphosphate solution (50g $(NaPO_3)_6L^{-1}$) for 16 to 18

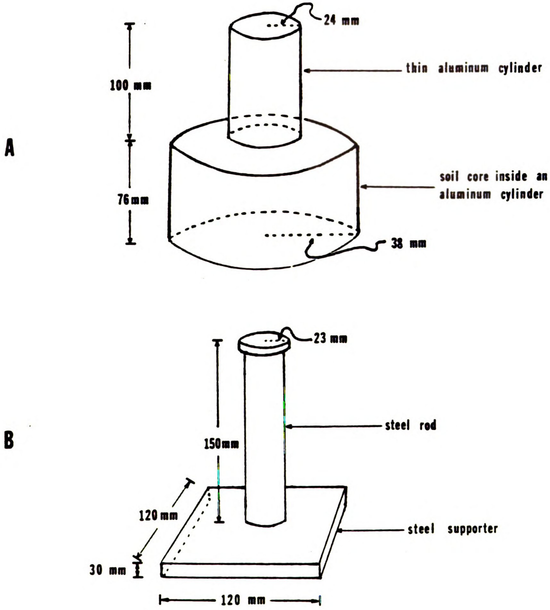


Figure 3. Instruments for sampling soil-root cores for the greenhouse experiment. A, a harvested soil core with a thin aluminum cylinder at the top. B, a plunger to remove the sample from the thin aluminum cylinder.

hours. The dispersed aggregates were poured into the system (Figure 4) where air and water pressure (A) caused a separation of soil and roots as the suspension moved upward through the column (B). The suspension traversed section (C) finally collecting the roots on a 0.84 mm screen (D). A final washing was accomplished by transferring the roots from the 0.84 mm screen to a 0.42 mm screen (E). When all the soil had been removed, the roots were stored in sealed plastic bags in 100 mL of water containing 10% formaldehyde.

Root length per soil-root core volume for both field and greenhouse experiments was measured by the method of Newman (1966) using 0.41 by 0.36 m grid size and a counter. Root length density $m(m)^{-3}$ was determined by dividing root length by the soil-root core volume.

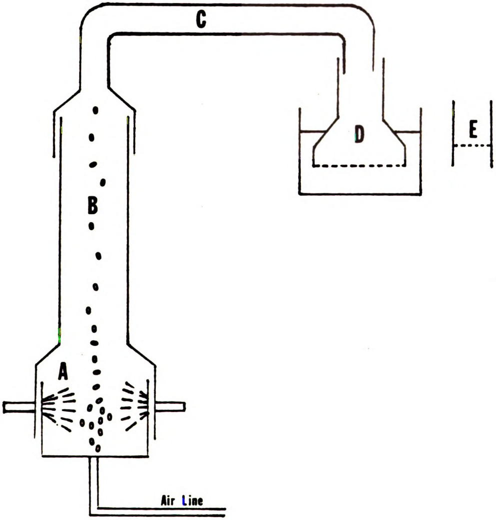


Figure 4. Part of the hydropneumatic electriation system for root separation from the soil-root sample. A through E are explained in the text. (Taken from Smucker, McBurney and Strivastava, 1982).

RESULTS AND DISCUSSION

I. Description of the Study

Soil structural modification as related to different cropping systems was studied on a pre-existing long term experiment. Disturbed and undisturbed soil samples were taken at different depths from selected cropping systems at different dates during the years of 1982 and 1983. The cropping systems were: C-B, Be-B, O-Be-B, C-C-C-B, C-Be-Be-B and O-A-Be-B. Some phenological measurements were also included for sugar beets during the growing season of 1983. The later measurements will assist in defining structural changes due to the cropping systems used.

A greenhouse experiment was conducted in 1983 on undisturbed soil cores at the same depths as those for undisturbed soil structural studies. Each core was planted with navy beans (Seafarer) to study the effect of soil structure on their root growth and relate that to the field measurements.

II. Soil Structural Studies

In order to understand the trend of change in soil structure with depth which may be related to the chosen systems, several indices were used. They included bulk density (BD), saturated hydraulic conductivity (SHC), total porosity (TP), air porosity (AP), stability of soil aggregates (AS) and their mean-weight diameters (MWD).

2.1. Undisturbed Samples

To represent field situations, undisturbed soil cores were sampled in October 1982, May and November 1983. During the first and second sampling dates all of the selected cropping system plots were used. On the third sampling date only corn-sugar beets (C-B), oats-navy beans-sugar beets (O-Be-B) and corn-navy beans-navy beans-sugar beets (C-Be-Be-B) systems were sampled. Four depths were used to measure BD, SHC, TP and AP. The later was measured at a moisture tension of 600 mm.

Each index was analyzed statistically where treatments were the whole plots of a randomized complete block design with depth as the sub-plot.

2.1.1. Bulk Density

The simple effect of soil depth on BD was significant for each sampling date (Table 3). It is

Table 3. Effect of soil sampling depth on bulk density (BD) in a cropping systems study for the three sampling dates.

Sampling Depth	Sampling Date		
	October 1982	May 1983	November 1983
m		Mg m^{-3}	
0 - 0.08	1.08†	1.15a ‡	1.20a
0.08 - 0.15	1.15	1.25b	1.24b
0.15 - 0.23	1.18	1.32c	1.27b
0.23 - 0.31	1.30	1.36d	1.35c

†Cropping system x depth interaction significant, see Table 4.

‡ Means followed by the same letter in a column are not significantly different at a probability level of 5% according to the Duncan's Multiple Range Test.

apparent that a general pattern of changes in BD have been followed with depth. The surface layer (0 to 0.08 m) had the lowest BD, and as the depth increased, BD increased to a maximum below the plow layer (0.23 to 0.31 m).

For the sampling date of October 1982, an interaction effect of cropping system X soil depth on BD was also significant (Table 4). The same trend of an increase in BD with depth was shown for each system. At the 0 to 0.08 m depth there was no difference among the cropping systems. Below the surface layer, variations among the systems became more evident as the depth increased. The navy beans-sugar beets (Be-B) system had the highest BD at depths within the plow layer (0 to 0.23 m). The lowest values for the same depths were shared between C-B and corn-corn-corn-sugar beets (C-C-C-B). At the same time, intermediate values were measured from O-Be-B, C-Be-Be-B and oats-alfalfa-navy beans-sugar beets (O-A-Be-B) systems. Below the plow layer differentiation among the systems started to disappear with the C-B system was less than the O-A-Be-B for the only significant difference.

2.1.2. Saturated Hydraulic Conductivity

Saturated hydraulic conductivity values were generally high due to boundary flow errors. The simple effect of soil depth on this index was significant for each sampling date (Table 5).

Table 4. Effect of cropping system and depth on soil bulk density (BD) in a cropping systems study for the October 1982 sampling date.

Cropping[†] System	Sampling Depth (m) 0-0.08	0.08-0.15	0.15-0.23	0.23-0.31
	$Mg\ m^{-3}$			
C-B	1.05a[‡]	1.15ab	1.16a	1.24a
Be-B	1.12a	1.21a	1.24b	1.29ab
O-Be-B	1.09a	1.13b	1.17ab	1.31ab
C-C-C-B	1.07a	1.13b	1.15a	1.30ab
C-Be-Be-B	1.07a	1.17ab	1.21ab	1.31ab
O-A-Be-B	1.08a	1.14ab	1.20ab	1.33b

[†] c = corn, BE = navy beans, B = sugar beets, O = oats, A = alfalfa.

[‡]Means followed by the same letter or letters in a column (for comparison of two cropping system means within one sampling depth) are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 5. Effect of soil sampling depth on saturated hydraulic conductivity (SHC) in a cropping systems study for the three sampling dates.

Sampling Depth	Sampling Date		
	October 1982	May 1983	November 1983
m	$kg\ s\ m^{-3}$		
0 - 0.08	23.2a†	21.5a	19.9a
0.08 - 0.15	22.8a	13.7b	18.4a
0.15 - 0.23	18.0b	8.95c	15.2a
0.23 - 0.31	6.86c	7.89d	2.52b

† Means followed by the same letter in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

All sampling dates showed a decrease in SHC with increasing depth, but variabilities among depths were present from one sampling date to the other. The interaction effect of sampling date X soil depth will be discussed in sub-subsection 2.3.2.

Within the plow layer (0 to 0.23 m), SHC showed more variability with depth on May 1983 than the other 2 dates. The October 1982 sampling measurements indicated that some changes in SHC occurred with depth, while November 1983 samples were more homogeneous.

The lowest values for SHC were measured from samples below the plow layer (0.23 to 0.31 m) for each sampling date. Between the surface layer (0 to 0.08 m) and below the plow depth (0.23 to 0.31 m) the reductions were 16.3, 13.6 and 17.4 units of SHC for October 1982, May and November 1983 sampling dates, respectively.

2.1.3. Total Porosity

The simple effect of soil depth on TP was significant for each sampling date (Table 6). The decrease in TP with depth was small for all sampling dates. Maximum changes were between the surface and below the plow layers (0 to 0.08 m and 0.23 to 0.31 m). Reductions of 12, 13 and 10% were measured between the two layers for October 1982, May and November 1983 sampling dates, respectively.

Table 6. Effect of soil sampling depth on total porosity (TP) in a cropping systems study for the three sampling dates.

Sampling Depth	Sampling Date		
	October 1982	May 1983	November 1983
m		%	
0 - 0.08	58.8a[†]	56.6a	54.7a
0.08 - 0.15	56.5b	52.9b	53.2b
0.15 - 0.23	55.2b	49.9c	52.2b
0.23 - 0.31	51.7c	49.2c	49.1c

[†] Means followed by the same letter in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

2.1.4. Air Porosity

Air porosity was measured with an air-pycnometer technique after the saturated soil core samples were equilibrated at 600 mm water tension. Due to the nature of the Charity clay soil and the large number of samples used it was felt that this arbitrary tension value would give some indication of the soil aeration porosity.

The simple effect of soil depth on AP was significant for each sampling date (Table 7). The surface layer (0 to 0.08 m) showed the highest values of AP. Beneath this layer, AP decreased significantly at each depth especially for the May and November 1983 sampling dates.

Relative to the surface layer, AP decreased by 36.6, 30.6 and 64.9 % at 0.08 to 0.15 m, 0.15 to 0.23 m and 0.23 to 0.31 m depths, respectively for October 1982 samples. Similarly, reductions of 40.1, 64.1 and 76.8% and 14.0, 30.7 and 58.8% were measured for May and November 1983 sampling dates, respectively.

2.2. Disturbed Samples

Soil samples collected during October 1982 and November 1983 at two depths (0 to 0.1 and 0.1 to 0.2 m) were used for aggregate analysis by the wet-sieving method. The first sampling date included all the six systems used in this study, while the second sampling date included only C-B, O-Be-B and C-Be-Be-B systems.

Table 7. Effect of soil sampling depth on air porosity (AP) in a cropping systems study for the three sampling dates.

Sampling Depth	Sampling Date: October 1982	May 1983	November 1983
m	%		
0 - 0.08	26.8a†	23.2a	22.8a
0.08 - 0.15	18.6b	13.9b	19.6b
0.15 - 0.23	17.0b	8.32c	15.8c
0.23 - 0.31	9.41c	5.37d	9.39d

† Means followed by the same letter in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

2.2.1. <u>Mean-Weight Diameter</u>

The mean-weight diameters were significantly different between the two depths for each sampling date (Table 8). The data showed that MWD increased with depth by 52.8 and 59.6% for the first and second sampling dates, respectively.

The simple effect of cropping systems on MWD was also significant for each date (Table 9). From the data of October 1982 it is apparent that C-C-C-B had the highest MWD followed by C-B. Since the second sampling date did not include C-C-C-B, the highest MWD was measured from C-B system. For both dates the data indicated that higher

Table 8. Effect of soil sampling depth on mean-weight diameter (MWD) of soil aggregates in a cropping systems study sampled on October 1982 and November 1983.

Sampling Depth	Sampling Date	
	October 1982	November 1983
m	mm	
0 - 0.1	0.422a†	0.461a
0.1 - 0.2	0.645b	0.736b

† Means followed by the same letter in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 9. Cropping system effect on mean-weight diameter (MWD) of a Charity clay soil in a cropping systems study sampled on October 1982 and November 1983.

Treatment†	Sampling Date	
	October 1982	November 1983
	mm	
C-B	0.550ab‡	0.698a
Be-B	0.488a	--
O-Be-B	0.503a	0.524b
C-C-C-B	0.674b	--
C-Be-Be-B	0.499a	0.572b
O-A-Be-B	0.490a	--

† C = corn, B = sugar beets, Be = navy beans, O = oats and A = alfalfa.

‡ Means followed by the same letter or letters in a column are not significantly different at a 5% probability level according to Duncan's Multiple Range Test.

values of MWD were associated with systems which contained a higher percent of corn in their cropping system.

2.2.2. Aggregate Stability

The ability of soil aggregates to withstand destructive forces caused by water is very important in preserving good soil structure. Aggregate stability was measured by the wet sieving method (subsection 4.2 of the MATERIALS AND METHODS) by which the percent distribution of aggregates for 7 different aggregate size ranges (5 to 4, 4 to 2, 2 to 1, 1 to 0.5, 0.5 to 0.25, 0.25 to 0.106 and < 0.106 mm) were determined at two soil depths (0 to 0.1 and 0.1 to 0.2 m).

Total aggregate stability which included all size ranges was also determined at the two depths. A statistical analysis was done to measure the effect of cropping system, soil depth and their interaction on total AS. For each sampling date, only the effect of soil depth was significant (Table 10). Aggregates were more stable for the 0.1 to 0.2 m than at 0 to 0.1 m soil depth.

In order to have a broader perspective about aggregate stability, another statistical analysis was done to measure the effect of cropping system, soil depth, aggregate size range and their interaction on the percentage distribution of aggregates for each sampling date. The data

Table 10. Effect of soil sampling depth on aggregate stability (AS) of a Charity clay soil in a cropping systems study sampled on October 1982 and November 1983.

Sampling Depth	Sampling Date	
	October 1982	November 1983
m	%	
0 - 0.1	73.2a†	77.3a
0.1 - 0.2	83.9b	85.6b

†Means followed by the same letter in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

were analyzed as split-plot with crop system the main plot, depth the subplot and aggregate size range the sub-subplot.

The percentage of aggregates less than 0.5 mm in size appeared to be higher than the larger aggregates in October 1982 in the surface soil (Figure 5). However, samples from 0.1 to 0.2 m depth seemed to have a high percentage of aggregates for the two size ranges between 1 and 0.25 mm (Figure 6).

There was a tendency for cropping systems with high percentages of corn to contain more aggregates for the size ranges between 5 to 2 mm. But the trend of change in aggregates size distribution among the cropping systems was not clear as indicated by the statistical analysis.

The November 1983 sampling indicated that all the cropping systems seemed to have a high percentage of aggregates of the size range 0.5 to 0.25 mm at the 0 to 0.1 m soil depth (Figure 7). Meanwhile, samples from the 0.1 to 0.2 m depth appeared to have high percentages of aggregates for the two size ranges between 1 to 0.25 mm (Figure 8). For the two sampling depths, the percentage of aggregates for the size range 2 to 1 mm from the C-B system was higher than from the O-Be-B or C-Be-Be-B systems. The reverse relation was established for the aggregate size range 0.25 to 0.106 mm.

The results for the two depths were pooled and analyzed statistically in order to measure the effect of

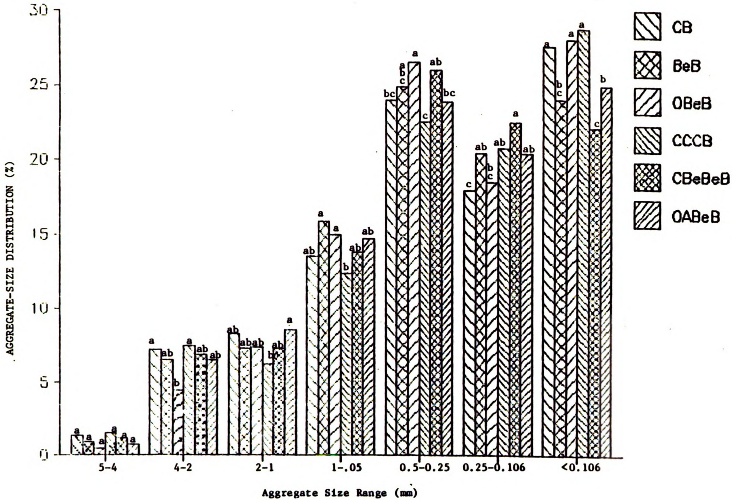


Figure 5. Influence of cropping systems on aggregate size distribution sampled from 0 to 0.1 m soil depth on October 1982. Bars with the same letter are not significantly different at 0.05 probability level based on Duncan's Multiple Range Test (for comparison of two cropping system means within an ASR).

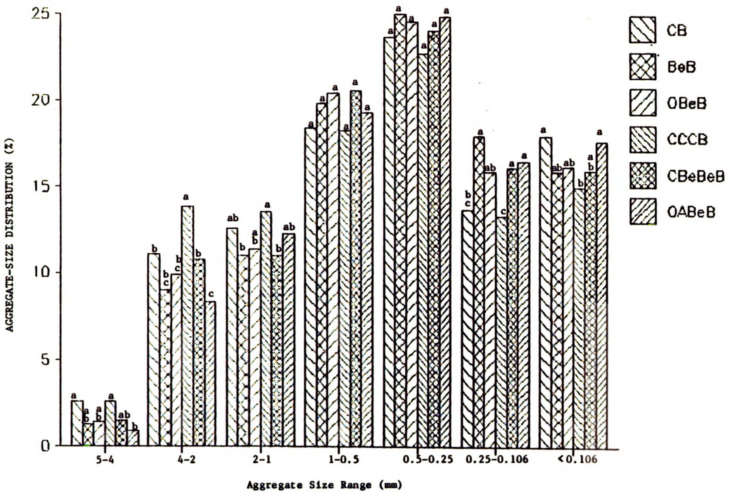


Figure 6. Influence of cropping systems on aggregate size distribution sampled from 0.1 to 0.2 m soil depth on October 1982. Bars with the same letter are not significantly different at 0.05 probability level based on Duncan's Multiple Range Test (for comparison of two cropping system means within an ASR).

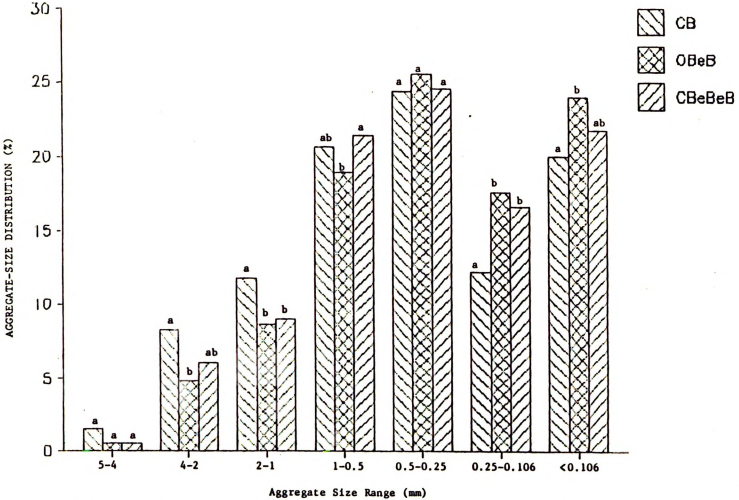


Figure 7. Influence of cropping systems on aggregate size distribution sampled from 0 to 0.1 m soil depth on November 1983. Bars with the same letter are not significantly different at 0.05 probability level based on Duncan's Multiple Range Test (for comparison of two cropping system means within an ASR).

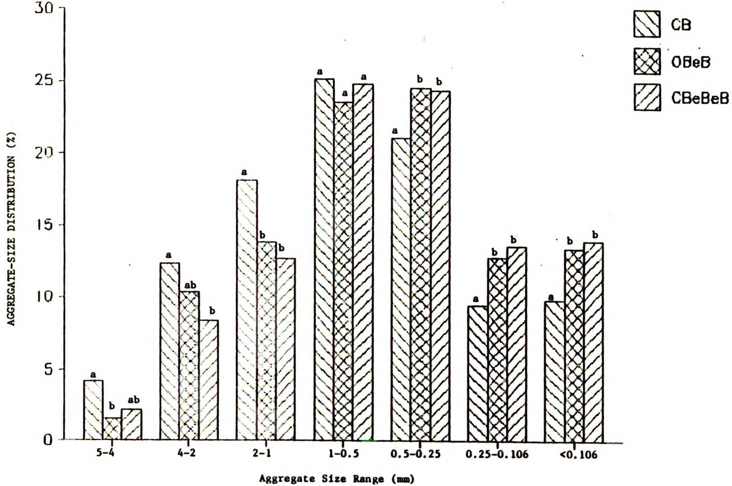


Figure 8. Influence of cropping systems on aggregate size distribution sampled from 0.1 to 0.2 m soil depth on November 1983. Bars with the same letter are not significantly different at 0.05 probability level based on Duncan's Multiple Range Test (for comparison of two cropping system means within an ASR).

cropping systems, aggregate size range and their interaction on aggregate size distribution within the entire plow layer. The simple effect of aggregate size range was significant for the October 1982 sampling (Table 11) and the interaction was significant for the November 1983 sampling (Figure 9).

2.3. Changes Over Time

In order to evaluate changes in structure indices with time, a combined analysis was done on three cropping systems. These systems were selected on the basis of percentage corn in the cropping system and were O-Be-B, C-Be-Be-B and C-B or 0, 25 and 50% corn, respectively. Bulk density, SHC, TP and AP were evaluated for all three sampling dates and MWD and AS were evaluated for the October 1982 and November 1983 sampling dates. The data were analyzed as a split-plot design with sampling date as the main plot, cropping system as the subplot and depth as the sub-subplot.

The probability of a significant F test is shown in Table 12. The 3-way interaction among date, cropping system and depth was not significant for any of the parameters measured. Only the simple effects or the 2-way interactions are presented.

Table 11. Aggregate size ranges and their distribution in a Charity clay soil in a cropping systems study sampled on October 1982 and November 1983.

Aggregate size Range	Aggregate Size Distribution October 1982	November 1983
mm	%	
5 - 4	1.8a†	1.6‡
4 - 2	8.1b	9.0
2 - 1	9.1b	12.4
1 - 0.5	16.bc	21.2
2.5 - 0.25	24.5d	23.9
0.25 - 0.106	17.8c	13.4
<0.106	22.0e	18.6

†Means followed by the same letter or letters in a column are not significantly different at a 5% probability level according to Duncan's Multiple Range Test.

‡ Cropping system x aggregate size range interaction significant, see Figure 9.

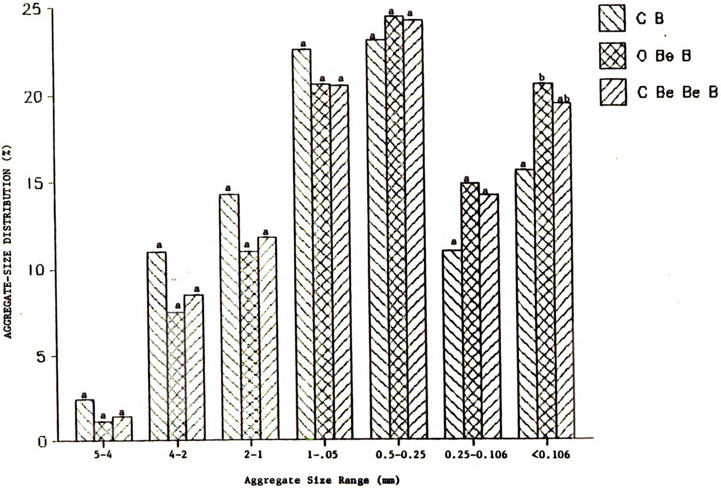


Figure 9. Effect of cropping system X ASR interaction on the size distribution of aggregates sampled on November 1983. Bars with the same letter are not significantly different at 0.05 probability level based on Duncan's Multiple Range Test (for comparison of two cropping system means within an ASR).

Table 12. Probability of a significant F test for various soil structural indices combined over the different sampling dates.

Source of variation	BD	SHC	TP	AP	MWD	AS
Date	*	NS	*	*	NS	NS
Cropping System (T)	NS	NS	NS	NS	*	NS
Depth (D)	*	*	*	*	*	*
T x D	NS	NS	NS	NS	NS	NS
Date x D	*	*	*	*	NS	NS
Date x T	*	NS	*	NS	NS	NS
Date x T x D	NS	NS	NS	NS	NS	NS

2.3.1. Bulk Density

The interaction between depth of sampling and date of sampling will be evaluated for the effects of date within a depth. The simple effect of depth within a single date has been presented in sub-subsection 2.1.1.

The general pattern of increase in BD with depth was followed for all sampling dates (Table 13). At the same time, the magnitude of increase was different from one sampling date to the other depending on the sampling date. At the end of the first 7 month period (October 1982 to May 1983) BD increased by 6.5, 8.7, 11.8 and 6.2% for the 0 to 0.08, 0.08 to 0.15, 0.15 to 0.23 and 0.23 to 0.31 m depths, respectively. Changes in BD with depth were not consistent for the second 6 month period (May to November 1983). When soil samples were taken 13 months after the first sampling date (October 1982), BD increased by 12.2, 7.8, 6.8 and 5.5% for the consecutive depths, respectively.

The interaction between cropping system and sampling date appeared to be due to a larger change in BD from October 1982 to May 1983 for the C-B system than for the other two systems (Table 14).

From October 1982 to May 1983, BD increased by 11.4 8.5 and 5% for the C-B, O-Be-B and C-Be-Be-B cropping systems, respectively. However, there was no change between the May and November 1983 sampling dates.

Table 13. Effect of sampling date and depth on bulk density (BD) of a Charity clay soil in a cropping systems study.

Sampling Date	Depth of Sampling (m) 0-0.08	0.08-0.15	0.15-0.23	0.23-0.31
	$Mg\ m^{-3}$			
October 1982	1.07a†	1.15a	1.18a	1.28a
May 1983	1.14b	1.25b	1.32b	1.36b
November 1983	1.20c	1.24b	1.26c	1.35b

†Means followed by the same letter in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 14. Effect of sampling date and cropping system on bulk density (BD) of a Charity clay soil in a cropping systems study.

Sampling Date	Cropping System†		
	CB	OBeB	CBeBeB
		$Mg\ m^{-3}$	
October 1982	1.14a‡	1.18a	1.19a
May 1983	1.27b	1.28b	1.25b
November 1983	1.27b	1.25b	1.27b

† C = corn, B = sugar beets, O = oats, Be = navy beans

‡Means followed by the same letter in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Even though the 3-way interaction was not significant, a plot of those data shows an interesting pattern (Figure 10). It is apparent that more convergence of the cropping systems with respect to sampling depth occurred as the sampling dates progressed. This aspect will be discussed in sub-section 2.4.

2.3.2. Saturated Hydraulic Conductivity

The swelling and shrinkage characteristics of Charity clay soil in combination with boundary flow errors resulted in high values of SHC. The sampling date x soil depth interaction on SHC was significant (Table 15), while the simple effect of depth for each sampling date was presented previously (sub-subsection 2.1.2.).

The major changes in SHC with sampling date occurred at the 0.08 to 0.15 and 0.15 to 0.23 m depths. Seven months after the first sampling date, SHC decreased by about 42% at 0.08 to 0.15 m soil depth, then increased by 36% six months later. For the same periods, SHC decreased by 55% and increased by 85% at 0.15 to 0.23 m depth.

2.3.3. Total Porosity

Since TP was calculated on the basis of bulk density $[(1 - \frac{BD}{2.65}) \times 100]$, the pattern of changes in TP with either depth or cropping system followed that of BD. The

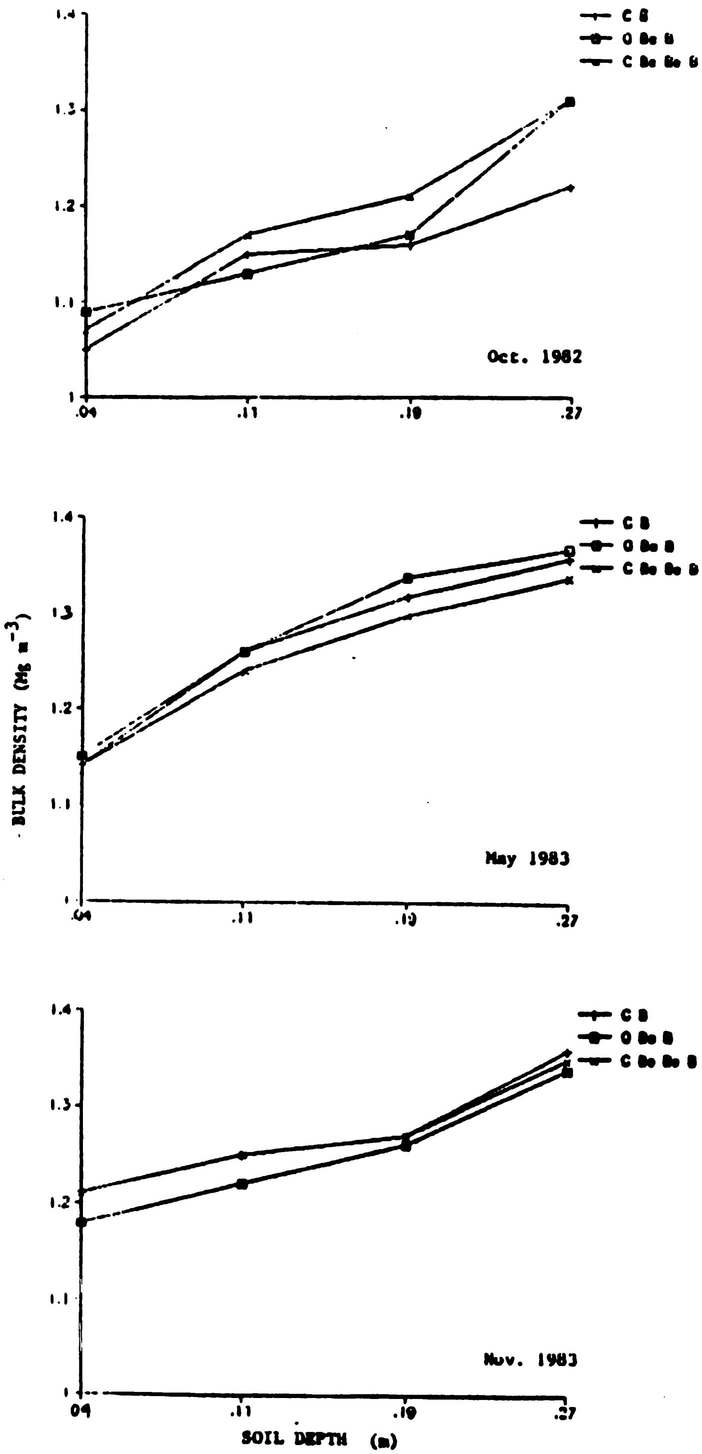


Figure 10. Variations in BD among the different cropping systems as affected by depth for the three sampling dates.

Table 15. Effect of sampling date and depth on saturated hydraulic conductivity (SHC) of a Charity clay soil in a cropping systems study.

Sampling Date	Depth of Sampling (m)			
	0-0.08	0.08-0.15	0.15-0.23	0.23-0.31
	kg s m^{-3}			
October 1982	20.8a†	22.2a	17.6a	7.1a
May 1983	20.4a	12.8b	8.2b	7.6b
November 1983	19.9a	18.4ab	15.2a	2.5a

†Means followed by the same letter in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

interaction of sampling date x soil depth on TP was significant (Table 16).

Most of the changes in TP occurred at the 0 to 0.08 m soil depth. Total porosity decreased by 4.5 and 4.4% from October 1982 to May 1983 and from May to November 1983, respectively at that depth. At 0.08 to 0.15, 0.15 to 0.23 and 0.23 to 0.31 m soil depths, TP decreased by 6.7, 8.5 and 5.4%, respectively from October 1982 to May 1983 with negligible changes between May and November 1983. From October 1982 to November 1983, TP decreased by 8.7, 6.0, 5.8 and 5.0% at the four consecutive depths.

The interaction of sampling date x cropping system on TP was also significant (Table 17). Total porosity decreased by 7.6, 7.2 and 4.2% from October 1982 to May 1983 in plots from the C-B, O-Be-B and C-Be-Be-B cropping systems, respectively. Changes in TP between May and November 1983 were negligible for all the cropping systems. Regardless of the interaction effect, all cropping systems had acceptable ranges of TP for crop production at all sampling dates.

2.3.4. Air Porosity

The interaction effect of sampling date x soil depth on AP was significant (Table 18), while the simple effect of soil depth for each sampling date was presented in sub-subsection 2.1.4.

Table 16. Effect of sampling date and depth on total porosity (TP) of a Charity clay soil in a cropping systems study.

Sampling Date	Depth of Sampling (m) 0-0.08	0.08-0.15	0.15-0.23	0.23-0.31
	%			
October 1982	59.7a[†]	56.6a	55.4a	51.6a
May 1983	57.0b	52.8b	50.7b	48.8b
November 1983	54.5c	53.2b	52.2b	49.0b

[†]Means followed by the same letter in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 17. Effect of sampling date and cropping system on total porosity (TP) of a Charity clay soil in a cropping systems study.

Sampling Date	Cropping System†		
	CB	OBeB	CBeBeB
		%	
October 1982	56.7a‡	55.6a	55.2a
May 1983	52.4b	51.6b	52.9b
November 1983	51.9b	52.7b	52.0b

† C = corn, B = sugar beets, O = oats, Be = navy beans

‡ Means followed by the same letter in a column (for comparison of two sampling date means within a cropping system) are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 18. Effect of sampling date and depth on aeration porosity (AP) of a Charity clay soil in a cropping systems study.

Sampling Date	Depth of Sampling (m) 0-0.08	0.08-0.15	0.15-0.23	0.23-0.31
	%			
October 1982	27.3a†	18.8a	17.4a	9.8a
May 1983	22.9b	13.6b	7.9b	5.1b
November 1983	22.7b	19.7a	15.8a	9.2a

†Means followed by the same letter in a column (for comparison of two sampling date means within a depth) are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Air porosity decreased by 16.1, 27.7, 54.6 and 48.0% from October 1982 to May 1983 for the 4 consecutive depths. From May to November 1983, AP increased to values close to those from the first sampling date at 0.08 to 0.15, 0.15 to 0.23 and 0.23 to 0.31 m depths with negligible change at 0 to 0.08 m.

2.3.5. Aggregate Stability

The interaction effect of sampling date x aggregate size on aggregate size distribution was significant (Table 19). In November 1983, the distribution percentage was 3.5 and 4.6% higher than October 1982 samples for the aggregate size ranges of 2 to 1 and 1 to 0.5 mm, respectively. Meanwhile, in October 1982 the soil samplings contained more aggregates of smaller size (0.25 to 0.106 and < 0.106 mm). This means that part of the fine aggregates were regrouped to form larger aggregates during the thirteen month period.

Combined analysis for the two sampling dates indicated that cropping system x aggregate size range interaction on aggregate distribution was also significant (Figure 11). The percentage distribution of aggregates between 5 to 1 mm seemed to be higher in plots from C-B than from O-Be-B or C-Be-Be-B cropping systems. The percentage of aggregate size distribution was reversed for aggregates <0.5 mm in diameter. That is, the percent of aggregates

Table 19. Effect of aggregate size range and sampling date on aggregate size distribution of a Charity clay soil in a cropping systems study.

Aggregate size Range	Date of Sampling	
	October 1982	November 1983
mm	%	
5 - 4	1.6a[†]	1.6a
4 - 2	8.0a	9.0a
2 - 1	8.9a	12.4b
1 - 0.5	16.6a	21.2b
2.5 - 0.25	24.6a	23.9a
0.25 - 0.106	18.2a	13.4b
< 0.106	22.2a	18.6b

[†]Means followed by the same letter in a row are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

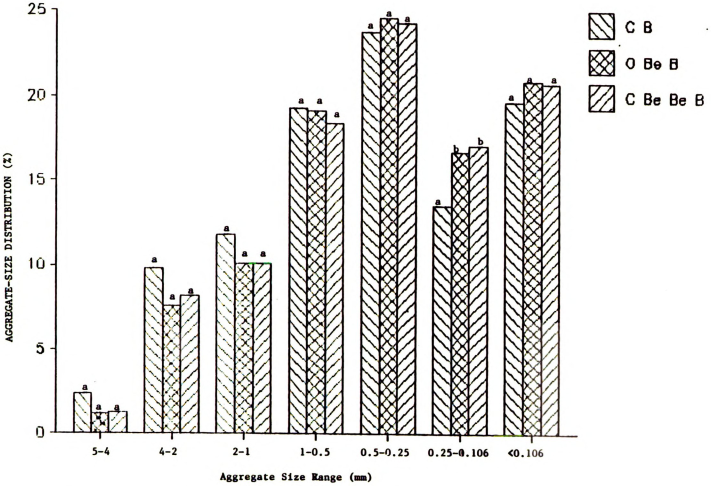


Figure 11. Aggregate size distribution as affected by aggregate size range for three cropping systems, averaged across the October 1982 and November 1983 sampling dates. Bars with the same letter are not significantly different at 0.05 probability level based on Duncan's Multiple Range Test (for comparison of two cropping system means within an ASR).

of size range 0.25 to 0.106 mm were higher in plots from O-Be-B or C-Be-Be-B systems than in those from the C-B systems.

2.4. Discussion

The simple effect of depth for all indices was significant for each sampling date. On the other hand, the effect of cropping system or cropping system x soil depth interaction varied from one sampling date to the other. Therefore, each sampling date will be discussed separately to understand what factors might have affected soil structure.

The interactive effects of sampling date x soil depth or sampling date x cropping system on some of the indices emphasize the dynamic process of soil structure modification. Therefore, in order to understand the changes in soil structure with time, the structural indices combined over all sampling dates, will also be discussed.

2.4.1. October 1982 Sampling Date

The simple effect of depth on all measured indices was significant, while the effect of system and/or system x soil depth varied among the indices (Table 20).

The data indicated that BD (Table 3), MWD (Table 8) and total AS (Table 10) increased with soil depth, while SHC (Table 5), TP (Table 6) and AP (Table 7) have decreased.

Table 20. Probability of a significant F test for various soil structural indices for the October 1982 sampling date.

Source	BD	SHC	TP	AP	MWD	AS
Depth(D)	*	*	*	*	*	*
Cropping System (T)	*	NS	*	NS	*	NS
T x D	*	NS	NS	NS	NS	NS

Degradation of larger aggregate sizes to smaller aggregates and/or alteration of pore size distribution probably were the reasons for these changes.

Previous studies indicated that at a BD of 1.0 to 1.2 Mg m^{-3} and a TP of 55 to 60%, soil conditions will be most favorable for plant growth and development (Kusnetsova, 1979). Accordingly, results from the plow layer (0 to 0.23 m) in this study suggest that BD and TP are not limiting yields. Below the plow layer depth (0.23 to 0.31 m), values of AP <10% were observed. This value of AP was considered by Baver and Fransworth (1940) as a critical value for sugar beet growth.

Reductions in SHC and AP below the plow layer were probably due to the formation of a plow pan by the mold board plowing operation. It has been found that the action of plowing presses soil aggregates together which results in a dense subsoil (Baver, Gardner and Gardner, 1972).

The simple effect of cropping system on MWD was significant (Table 9). It seems that a system which had corn as 50% or more of the rotating crops had the largest MWD. Apparently the amount of organic matter returned to the soil from each treatment played a significant role in increasing the MWD of soil aggregates. When the soil percent carbon and C/N ratio from various cropping systems (Zielke, 1983) were plotted against the measured MWD, good correlations were obtained (Figure 12). This indicates that

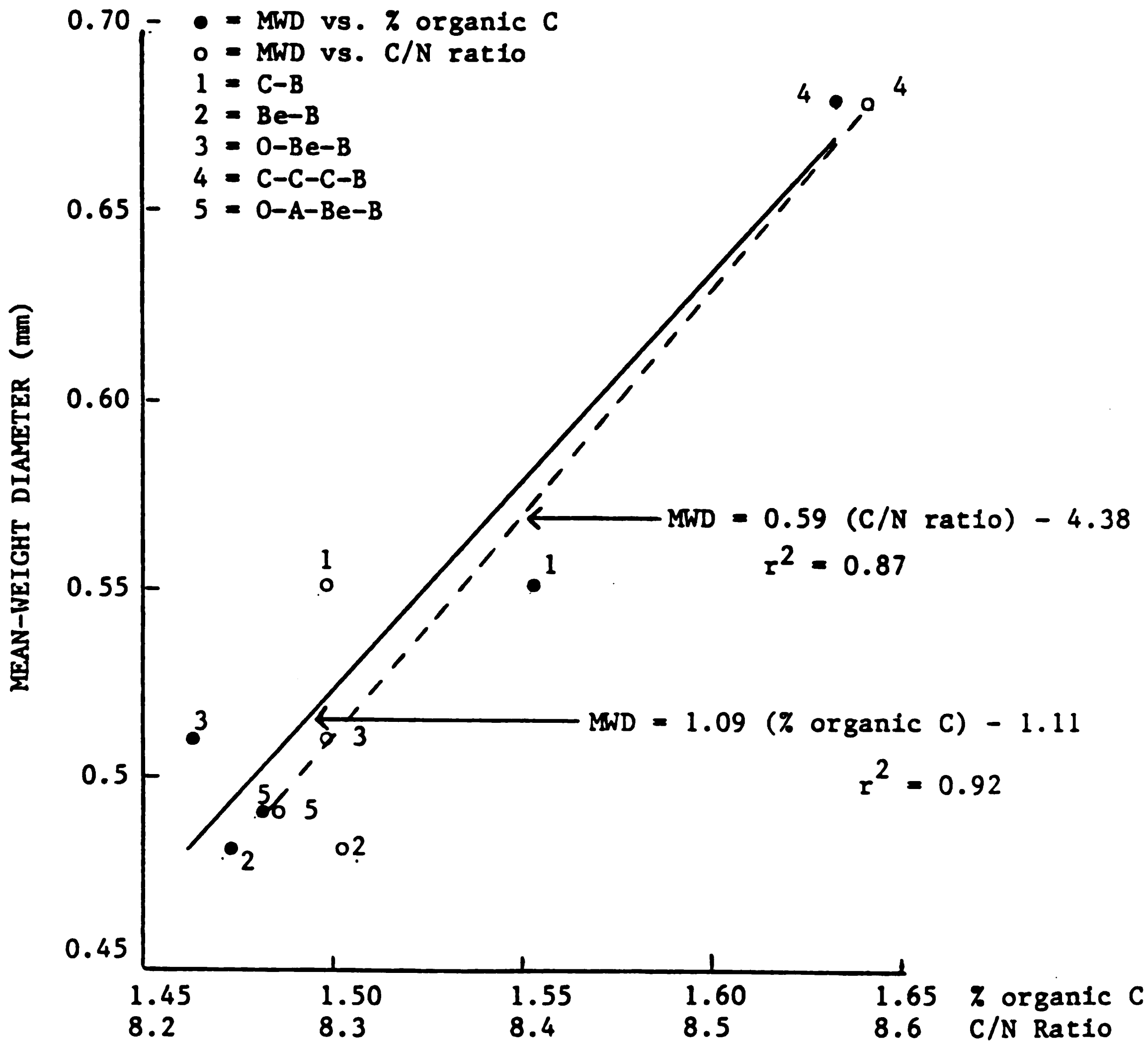


Figure 12. Aggregate mean-weight diameter (MWD) as affected by percent organic C and C/N ratio of the soil.

more organic matter has been returned to the soil from cropping systems with high percent of corn (C-B and C-C-C-B) and consequently has resulted in a larger MWD than the other treatments.

The cropping system x soil depth interaction on BD was significant (Table 4). Most of the changes in BD among cropping systems occurred within the plow layer (0 to 0.23 m). Even though BD increased with depth for all the systems, it is apparent that the percentage of corn in the system affected those changes. The C-C-C-B and C-B systems had lower BD than Be-B system at 0.08 to 0.15 and 0.15 to 0.23 m soil depths, respectively. The larger amounts of organic matter returned from the first two systems might have a significant role in decreasing BD.

2.4.2. May 1983 Sampling Date

Only the simple effect of soil depth was significant for the four indices measured at this sampling date (Table 21).

Bulk density increased with increasing depth (Table 3) which resulted in decreasing SHC (Table 5), TP (Table 6) and AP (Table 7). An increase in BD by about 15% at 0.15 to 0.23 m soil depth relative to the first depth (0 to 0.08 m) coincided in a reduction of AP of 64%. Similarly, reductions by 58% and 12% were measured for SHC and TP, respectively. This indicates that more changes have

Table 21. Probability of a significant F test for various soil structural indices for the May 1983 sampling date.

Source	BD	SHC	TP	AP
Depth (D)	*	*	*	*
Cropping System (T)	NS	NS	NS	NS
T x D	NS	NS	NS	NS

occurred within the plow layer depth during this sampling date.

2.4.3. November 1983 Sampling Date

Table 22 illustrates statistically the effect of the different sources of variability on the measured indices. Bulk density, SHC, TP, AP, MWD and AS were all significantly affected by soil depth (Tables 3, 5, 6, 7, 8 and 10, respectively). Meanwhile, cropping system effect was only significant for MWD (Table 9).

Sugar beets were grown during the 1983 season. Therefore, results from this sampling date could have been affected by the sugar beets root system. Changes in soil structural indices within the plow layer depth (0 to 0.23 m) followed a consistent trend with depth. That is, changes from one depth to another were not drastic. This means that modification of soil structure was uniform to a certain extent with depth. The deep tap roots of sugar beets and their numerous fibrous roots could have some effect. It is probable that the taproots pushed soil aside which resulted in a uniform BD, TP and SHC within the plow layer depth. At the same time, the fibrous roots would enhance the formation of a large number of small pores. Consequently, AP values were within an acceptable range for crop production (> 10%) as was suggested by Baver and Fransworth (1940).

Table 22. Probability of a significant F test for various soil structural indices for the November 1983 sampling date.

Source	BD	SHC	TP	AP	MWD	AS
Depth(D)	*	*	*	*	*	*
Cropping System (T)	NS	NS	NS	NS	*	NS
T x D	NS	NS	NS	NS	NS	NS

The significant effect of cropping system on MWD indicated that systems with a high percentage of corn had larger MWD than those with a lower percentage of corn or no corn at all in the cropping system.

2.4.4. Effect of Time on Soil Structure

The probability of a significant F test for the combined analysis of variance is reproduced as Table 23 (also shown as Table 12). Interactive effects of date x cropping system and/or date x depth were significant for BD, SHC, TP and AP while only simple effects of cropping system and/or depth were significant for MWD and AS.

During the first seven month period (October 1982 to May 1983) BD increased significantly at all depths (Table 13). As a result, TP and AP decreased at all depths (Tables 16 and 18, respectively) while SHC decreased only at 0.08 to 0.15 and 0.15 to 0.23 m soil depths (Table 15).

For the second six month period (May to November 1983) AP showed an increase to nearly the same values as the first sampling date (October 1982). The increase in AP occurred only below 0.08 m. During this period the slight decrease in BD and increase in AP could be the result of a combination of two factors. First, is the effect of sugar beet roots as explained in sub-subsection 2.4.3. The second factor might be the warmer temperature during that period. This in turn would enhance microbial activities

Table 23. Probability of a significant F test for various structural indices combined over the different sampling dates[†].

Source of Variation	BD	SHC	TP	AP	MWD	AS
Date	*	NS	*	*	NS	NS
Cropping System (T)	NS	NS	NS	NS	*	NS
Depth(D)	*	*	*	*	*	*
T x D	NS	NS	NS	NS	NS	NS
Date x D	*	*	*	*	NS	NS
Date x T	*	NS	*	NS	NS	NS
Date x T x D	NS	NS	NS	NS	NS	NS

[†]This is Table 12 reproduced for easy reference.

which would help in improving soil structure, especially below 0.08 m depth. On the other hand, during the first period, freezing and thawing and wetting and drying would result in smaller size aggregates which would fill the large pores and increase the soil weight per unit volume. As a result TP and AP decreased at all depths while SHC decreased at 0.08 to 0.15, and at 0.15 to 0.23 m soil depths.

The swelling and shrinkage characteristics of Charity clay soil could have resulted in differential changes in its structure. This would result in an uneven distribution of pore sizes which in turn would affect the aeration porosity (Baver, Gardner and Gardner, 1972). As a result, fluctuation in AP occurred due to the changes in aggregate size distribution which was indicated between October 1982 and November 1983 (Table 19). The resultant change in aggregate size distribution was an accumulation of finer aggregates below the plow layer (0.23 to 0.31 m) which decreased AP at that depth as well as reducing its change among the sampling dates.

Changes in SHC within the plow layer followed the same pattern as that of AP. This was expected since the hydraulic conductivity would be affected somewhat by soil characteristics such as distribution of pore sizes (Hillel, 1982).

The results indicated that the MWD was larger in cropping systems which had a higher percentage of corn.

Also, the C-B system contained a higher percent of aggregates with diameters ranging from 5 to 0.5 mm (Figure 11). The MWD is an average value and therefore gives a larger weight to large size aggregates. Therefore, in relating cropping system effects on soil structure care should be exercised not to depend solely on MWD alone.

During the first seven month period, all cropping systems showed an increase in BD (Table 14) and a decrease in TP (Table 17). The magnitude of change in BD from the three systems followed the order; C-B > O-Be-B > C-Be-Be-B while for TP the order was C-B = O-Be-B > C-Be-Be-B. Six months later, no significant differences occurred. Thirteen months after the first sampling date, the magnitude of change in BD and TP was higher in C-B system than either O-Be-B or C-Be-Be-B systems which were almost equal.

It seems that changes in BD and TP followed that of AS. The percent of aggregates <0.05 mm in diameter were higher in October 1982 than in November 1983. As a result, lower BD and higher TP were measured in October 1982. Thirteen months later, small size aggregates were regrouped to larger aggregates in the C-B system. Meanwhile, the percentages of smaller aggregates increased in the O-Be-B and C-Be-Be-B systems. The formation of larger aggregates in the C-B system resulted in more changes in BD and TP. However, the breakdown of larger aggregates in the O-Be-B and C-Be-Be-B systems into smaller aggregates reduced those changes. These results indicate that the C-B system had the ability to modify soil structure (as measured by BD and TP) more than O-Be-B or C-Be-Be-B systems.

The interactive effect of sampling date x cropping system was not significant for either SHC or AP (Table 23). However, changes in SHC and AP among the three sampling dates appeared to be greater for the C-B and C-Be-Be-B systems than in the O-Be-B system (Figures 13 and 14).

As a conclusion for this section, the general effect of cultivation on soil structure was found to increase the percent of smaller aggregates (<1.0 mm in diameter) as shown in Figure 15. Even though statistical analysis was not made, differences among aggregate sizes from the cultivated and virgin areas are evident.

The extent to which cultivation could affect soil structure would depend upon among other factors the types of crops grown. Data from the present study indicated that cropping systems which had a high percentage of corn tended to increase the percent of larger aggregates. This in turn resulted in more fluctuation in soil structural indices with time. On the other hand, cropping systems which had a low percentage of corn (C-Be-Be-B) or no corn at all (O-Be-B) increased the percent of smaller aggregate size ranges. Consequently, fewer changes were observed on the measured indices from these systems.

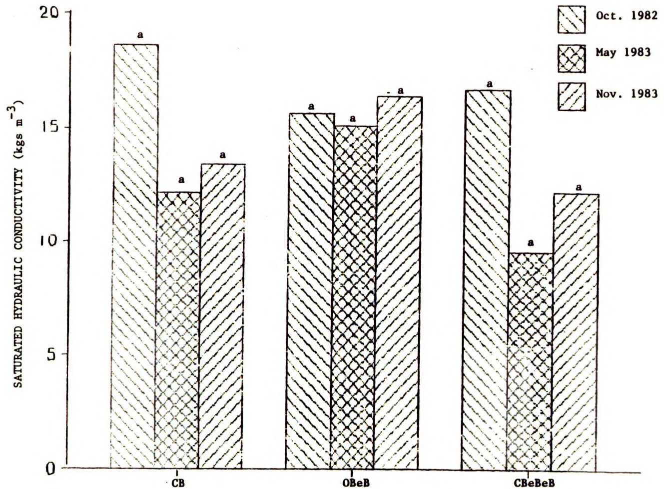


Figure 13. Influence of sampling date on saturated hydraulic conductivity for the different cropping systems. Bars with the same letter are not significantly different at 0.05 probability level based on Duncan's Multiple Range Test.

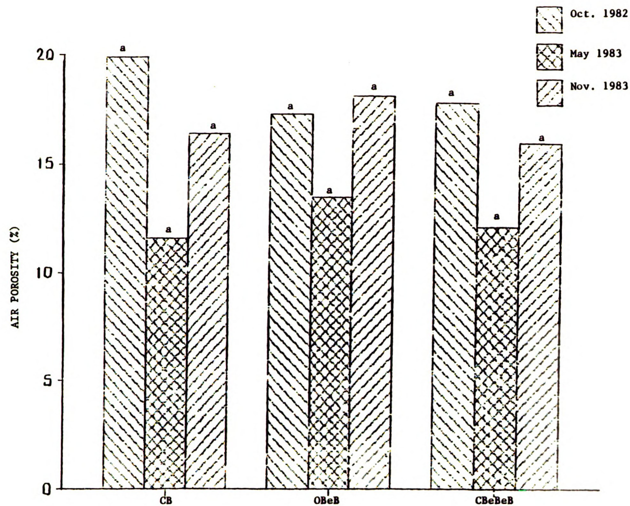


Figure 14. Influence of sampling date on air porosity at 600 mm water tension for the different cropping systems. Bars with the same letter are not significantly different at 0.05 probability level based on Duncan's Multiple Range Test.

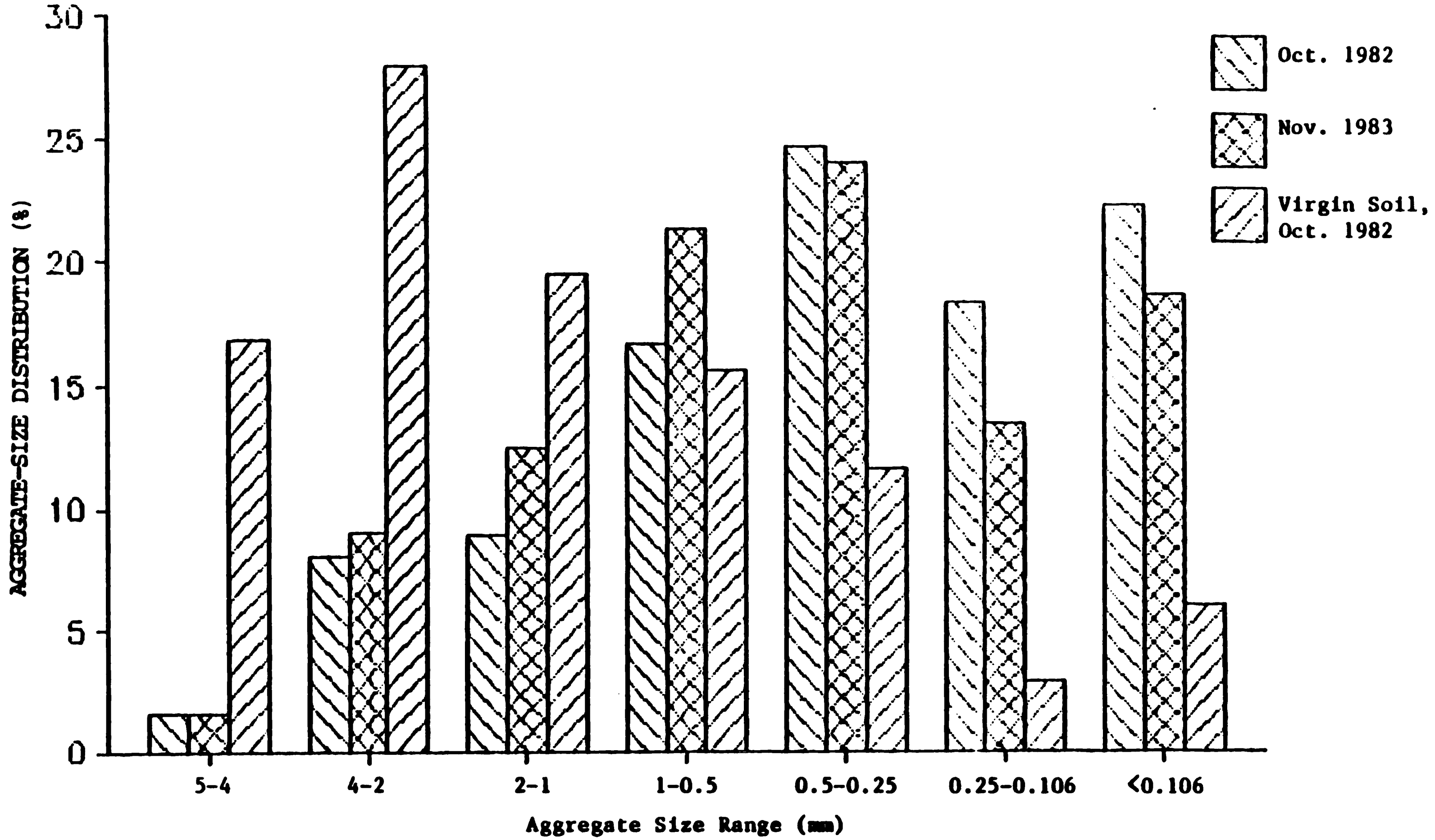


Figure 15. Comparisons of mean aggregate size distribution from three cropping systems (C-B, O-Be-B and C-Be-Be-B) sampled on two dates with that of an adjacent virgin soil sampled on October, 1982

III. Plant Indices and Crop Yield

Sugar beets (US H20) were grown during the 1983 season. Several plant parameters were measured at different dates to assist in studying cropping system effects in modifying soil structure.

The plant indices included leaf are index (LAI) and taproot-leaf weight ratio (TLWR) where all the six cropping systems were sampled. After sugar beet harvesting for yield and quality determinations, fibrous root lengths were measured at 6 different soil depths sampled from C-B, O-Be-B and C-Be-Be-B systems selected previously (section VII of the MATERIALS AND METHODS).

3.1. Leaf Area Index

The effect of cropping system on LAI was significant (Table 24). The lowest value was measured in the C-B system which was significantly different from those measured in either Be-B, C-Be-Be-B, or O-A-Be-B systems.

3.2 Taproot-Leaf Weight Ratio

The cropping system effect on TLWR calculated on dry and wet basis was significant for two sampling dates (Table 25). For July 25th sampling date, C-Be-Be-B system had a lower value of TLWR on wet weight basis than the C-B and C-C-C-B systems. For August 26th sampling, the C-Be-Be-B system also had the lowest value of TLWR on the wet weight

Table 24. Effect of cropping system on leaf area index (LAI) for sugar beets (US H20) in a cropping systems study sampled on August 26, 1983.

Cropping† System	LAI
C-B	1.68 a‡
Be-B	2.31 b
O-Be-B	1.82 ab
C-C-C-B	1.82 ab
C-Be-Be-B	2.32 b
O-A-Be-B	2.16 b

† C = corn, B = sugar beets, Be = navy beans, O = oats and A = alfalfa

‡ Means followed by the same letter or letters are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 25. Effect of cropping system on taproot-leaf weight ratio (TLWR) of sugar beets (US H20) on wet and dry basis in a cropping systems study sampled on different dates.

	Sampling Date			
	July 25, 1983		August 26, 1983	
Cropping System†	Wet	Dry	Wet	Dry
C-B	0.878 ab‡	2.02a	3.12 a	5.10 ab
Be-B	0.760 bc	1.86a	2.76 ab	4.34 b
O-Be-B	0.760 bc	1.94a	3.07 a	4.76 ab
C-C-C-B	0.935 a	2.23a	3.28 a	5.42 a
C-Be-Be-B	0.730 c	1.94a	2.72 b	4.19 b
O-A-Be-B	0.828 abc	1.85a	3.08 a	4.77 ab

† C = corn, B = sugar beets, Be = navy beans, O = oats, and A = alfalfa.

‡ Means followed by the same letter or letters in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

basis. Meanwhile, on dry weight basis, the C-C-C-B system had a higher TLWR than the Be-B and C-Be-Be-B systems with the latter having the lowest value.

3.3. Root Length Density

In order to determine root length density (RLD), bulk density (BD) and soil moisture percentage (MP), three soil cores (right, middle and left) between two sugar beet plants adjacently located in two rows were sampled. Each soil core taken was from a depth of 0.23 m to 0.69 m with a thickness of 0.08 m and then fractionated into subsamples 0.08 by 0.08 by 0.08 m.

Figure 16 shows the soil profile which was sampled from the inter-row space between the two plants and its 54 soil-root core subsamples. Bulk density, MP and RLD were measured in all the subsamples, however, the results were used in two ways. For the first one, measurements from all the subsamples were included in the statistical analysis. The second way utilized average values of the corresponding subsample numbers for the statistical analysis while the inner subsamples of the middle soil-root core were discarded to minimize the overlapping effect of the fibrous roots (Figure 17).

The simple effect of soil depth on soil-root core bulk density, soil moisture content and RLD was significant (Table 26). It is apparent that RLD decreased with depth.

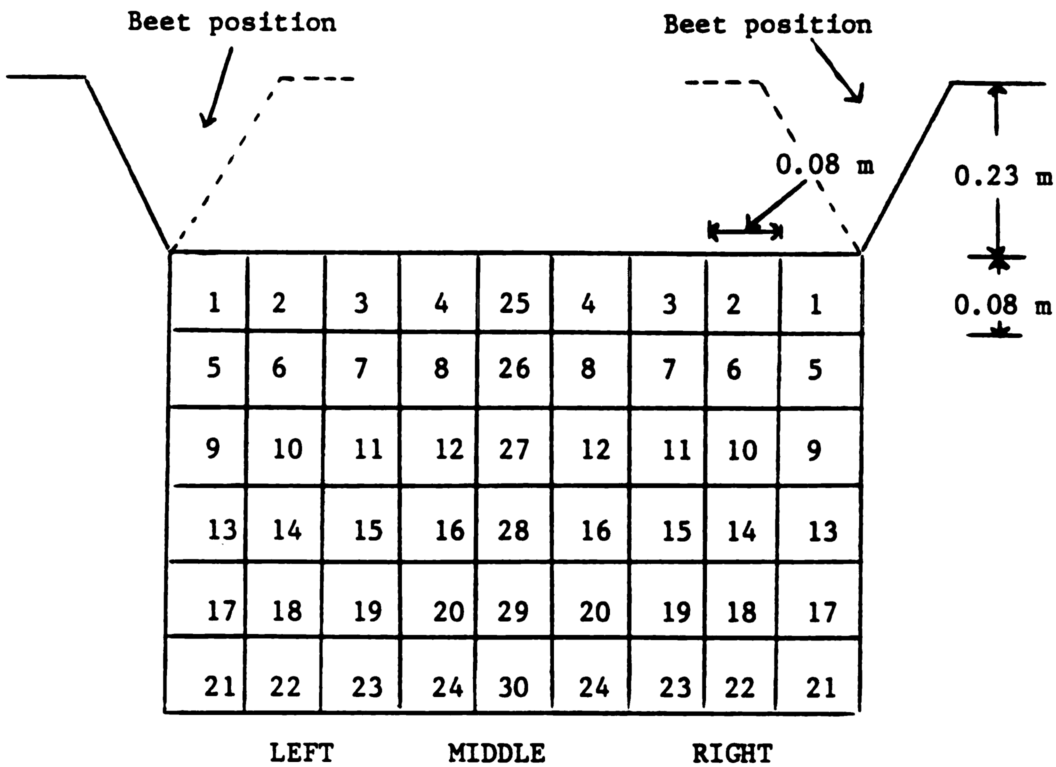


Figure 16. The inter-row space soil profile sampled with its 54 soil-root core subsamples after fractionation.

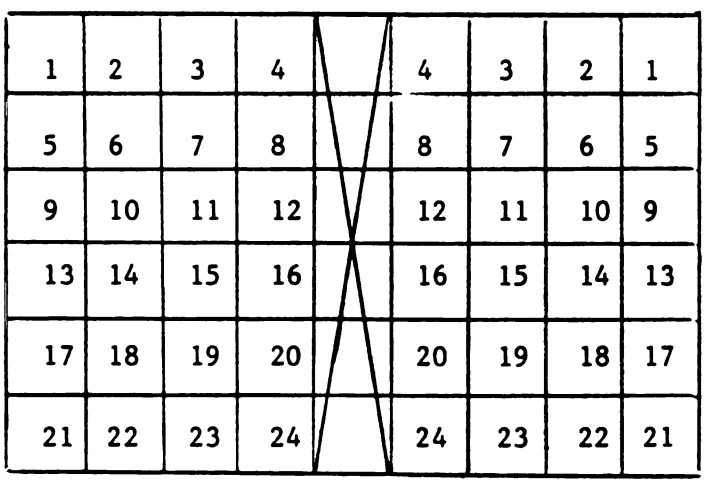


Figure 17. Diagramatic illustration for taking average measurements for each corresponding pair of soil-root core subsamples

Table 26. Effect of sampling depth on soil-root core bulk density (BD), moisture content (MP) and root length density (RLD) of sugar beets (US H20) in a cropping systems study sampled on October 1983.

Sampling Depth	BD	MP	RLD
m	Mg m^{-3}	%(v/v)	$m(m)^{-3}$
0.23-0.31	1.22 a†	32.4 ab	1.46 a
0.31-0.38	1.40 b	35.3 c	0.95 b
0.38-0.46	1.46 bc	34.5 c	0.74 c
0.46-0.53	1.51 cd	33.8 bc	0.61 cd
0.53-0.61	1.56 cd	33.4 abc	0.56 cd
0.61-0.69	1.52 cd	31.6 a	0.47 d

† Means followed by the same letter or letters in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Relative to the first depth, RLD decreased by about 35, 49, 58, 62 and 68% at 0.31 to 0.38, 0.38 to 0.46, 0.46 to 0.53, 0.53 to 0.61 and 0.61 to 0.69 m soil depth, respectively. Also, relative to the first depth, BD increased by 15, 20, 24, 28 and 25% at the five consecutive depths, while moisture content changed slightly with the lowest value at 0.61 to 0.69 m depth.

The changes in RLD among soil depths below the taproots were the result of the significant changes in the total root length distribution with depth (Table 27). Although the data in Table 27 included all the fibrous roots across the inter-row space they indicate that the longest roots were measured at the first depth (0.23 to 0.31 m) and that root length decreased with increasing depth.

The simple effect of the cropping system on net root length per plant (all the roots across the inter-row space) was significant (Table 28). This was reflected on RLD even after the overlapping of roots was minimized as shown in Table 29 where the cropping system effect on BD was also significant. The highest BD was measured in the C-Be-Be-B system where the RLD was the lowest relative to the other systems.

Although the effects of the cropping system and the sampling depth on RLD for the individual subsamples were not analyzed statistically, RLD distribution presented in Figures 18, 19, and 20 illustrate interesting patterns. It

Table 27. Root Length (RL) distribution of sugar beets (US H20) grown on a Charity clay soil in a cropping systems study sampled in October 1983.

Soil Depth	Root Length†
m	m
0.23-0.31	58.9 a‡
0.31-0.38	37.7 b
0.38-0.46	29.4 c
0.46-0.53	24.7 cd
0.53-0.61	22.4 cd
0.61-0.69	18.6 d

† Root length was measured in 3.95×10^{-3} m^3 soil below the taproot.

‡ Means followed by the same letter or letters are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 28. Influence of cropping system on fibrous root length of sugar beets (US H20) in a cropping systems study sampled in October 1983.

Cropping System[†]	Net Root Length
	m
C-B	231 a[‡]
O-Be-B	181 ab
C-Be-Be-B	163 b

[†] C = corn, B = sugar beets, O = oats, and Be = navy beans

[‡] Means followed by the same letter or letters are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 29. Influence of cropping system on soil-root core bulk density (BD) and root length density (RLD) of sugar beets (US H20) in a cropping systems study sampled on October 1983.

Cropping System[†]	BD	RLD
	Mg m^{-3}	$m(m)^{-3}$
C-B	1.45 ab[‡]	0.97 a
O-Be-B	1.42 a	0.75 ab
C-Be-Be-B	1.47 b	0.67 b

[†] C = corn, B = sugar beets, O = oats, and Be = navy beans.

[‡] Means followed by the same letter or letters in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

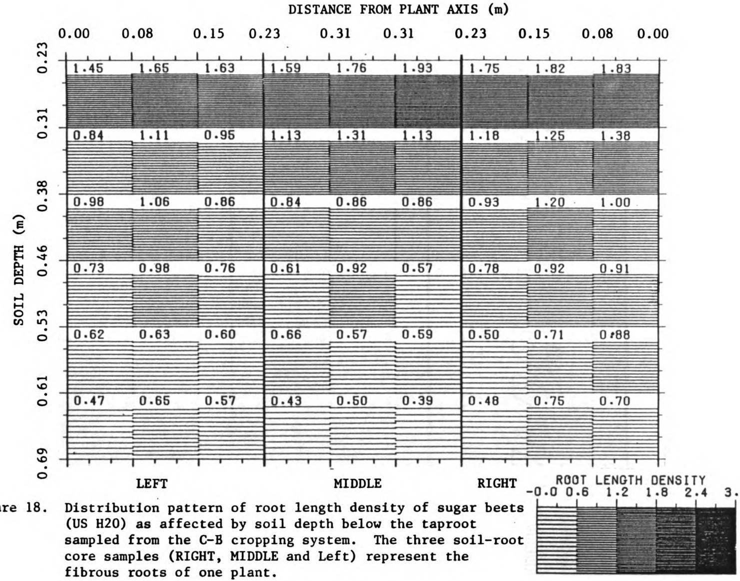
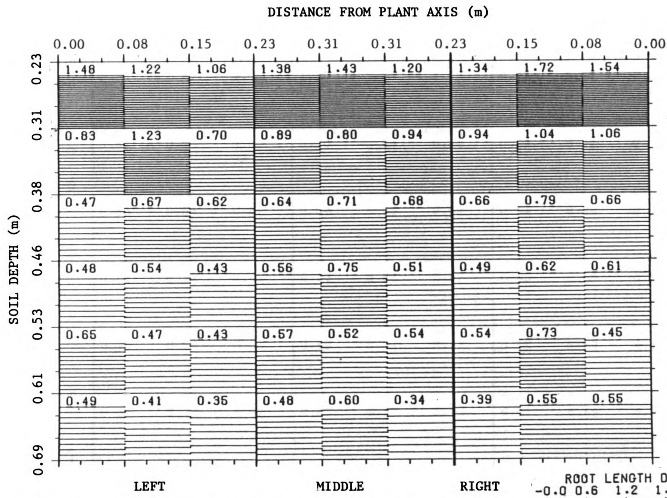


Figure 18. Distribution pattern of root length density of sugar beets (US H2O) as affected by soil depth below the taproot sampled from the C-B cropping system. The three soil-root core samples (RIGHT, MIDDLE and Left) represent the fibrous roots of one plant.



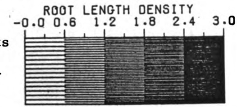


Figure 19. Distribution pattern of root length density of sugar beets (US H2O) as affected by soil depth below the taproot sampled from the O-Be-B cropping system. The three soil-root core samples (RIGHT, MIDDLE and LEFT) represent the fibrous roots of one plant.

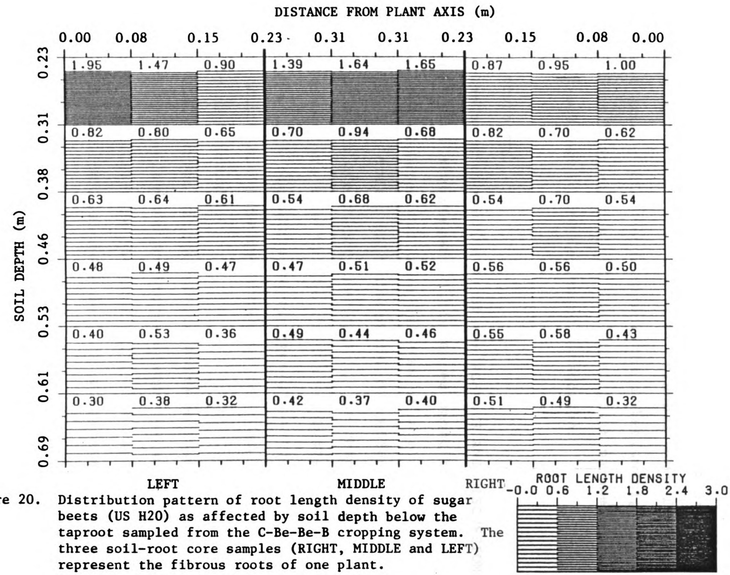


Figure 20. Distribution pattern of root length density of sugar beets (US H20) as affected by soil depth below the taproot sampled from the C-Be-Be-B cropping system. The three soil-root core samples (RIGHT, MIDDLE and LEFT) represent the fibrous roots of one plant.

is apparent that changes in RLD for each system at a specific depth were affected by the position of the subsample relative to the plant axis. There was a tendency for the fibrous root to have more branches away from the main root axis. This could affect the relationship among the fibrous root system and the other plant parameters as will be discussed in the following subsection.

3.4. Discussion

The data in section II of the RESULTS AND DISCUSSION indicated that significant differences among the cropping systems have occurred for some indices of soil structure. Therefore, in order to understand the effect of those changes on plant growth and development, the changes in the plant parameters due to the different systems will be discussed. The significance of variation in the plant indices which could be reflected on the final crop yield will also be discussed.

Discussions of the simple correlations among RLD (Sampled at different positions) and the other plant parameters will also be included. This will help to locate the proper sampling positions for roots in studying their role in plant growth and development.

3.4.1. Cropping System Effect on the Measured Indices

The data for the LAI parameter indicated that significant differences among the cropping systems occurred (Table 24). Sugar beets from the C-B system yielded smaller leaf areas than the C-Be-Be-B or the O-A-Be-Be systems. On the other hand, samples from the O-Be-B and the C-C-C-B systems yielded leaves of the same size which were not significantly different from the other systems.

Leaf area index was found to be highly affected by time, environmental factors, soil water and nutrients (Watson, 1952). Therefore, changes in LAI among the cropping systems planted under the same field conditions and sampled at a specific time can be related to the soil environment where soil structure plays a significant role. Moreover, the changes observed in the LAI would affect the CO_2 assimilation and respiration which could modify other plant growth parameters.

Results from the TLWR (the parameter which shows the whole plant performance) indicated that significant differences among the cropping systems occurred (Table 25). During the first sampling date (July 25, 1983) the cropping system effect was significant only when TLWR was calculated on the wet weight basis. Probably the smaller size of taproots as well as the succulency of the leaf blades and not the dry matter accumulation were the reason for those differences. However, the changes observed indicate that differences in the growth habits of sugar beets started to appear among the systems.

One month after the first sampling date, the cropping system effect was significant for both the wet and dry weight basis for TLWR (Table 25). The significant differences among the cropping systems were more pronounced for the dry weight basis where the TLWR from the C-C-C-B system was higher than those from the Be-B or the C-Be-Be-B systems.

Even though the LAI was not significantly different among the C-C-C-B, C-Be-Be-B and C-B systems, the order of magnitude was; C-C-C-B < C-Be-Be-B = Be-B. This means that the lower values of the LAI were accompanied by higher values of TLWR and vice versa. Therefore, the partition of the dry matter between the roots and the shoots would be different among the cropping systems.

The net root length per plant and the RLD index were significantly different among the systems (Tables 28 and 29, respectively). Sugar beets from the C-B system produced more fibrous roots per plant than from the C-Be-Be-B system which resulted in higher RLD. This means that the C-B system created good soil environmental conditions for root growth and development. As indicated in the previous section (section II), soil samples from the C-B system seemed to contain a higher percentage of large size soil aggregates than the C-Be-Be-B system. Consequently, the soil resistance for root growth in the C-B system would be low.

Root length density distribution patterns appeared to be different among the cropping systems (Figures 18, 19, and 20). At nearly all the sampling positions, the C-B system had higher values of RLD than the other systems which resulted in longer net root length per plant as indicated previously. All the cropping systems tended to have more fibrous roots away from their root axis which decreased with soil depth. Probably the less compacted soil in the inner-row space favored root growth away from the plant axis, while the increased compaction with depth decreased the penetration capacity for the fibrous roots. For example, relative to the first depth (0.23 to 0.31 m), the mean RLD at 0.31 to 0.38 m soil depth decreased by 33, 32 and 43% in the C-B, O-Be-B and C-Be-Be-B systems, respectively. These distribution within the soil profile could alter the relationships between the root system and the other plant parameters as will be seen in a later discussion.

3.4.2. Relationship Among Some Plant Parameters, Crop Yield and Quality

Table 30 illustrates the ratio of root length to TLWR, yield and RWS for the different cropping systems. Sugar beets in the C-B system had a higher ratio of root

Table 30. Effect of cropping systems on the ratio of root length (RL) to taproot-leaf weight ratio (TLWR), yield and recoverable white sugar (RWS) of sugar beets (US H20).

Cropping† System	RL:TLWR	RL:YIELD	RL:RWS
	m	$m(g)^{-1}$	
C-B	76.7a‡	0.899a	6.08a
O-Be-B	54.6b	0.613a	3.98a
C-Be-Be-B	52.6b	0.557a	3.68a

† C = corn, B = sugar beets, O = oats and Be = navy beans

‡ Means followed by the same letter in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

length to TLWR than in the O-Be-B or C-Be-Be-B systems. This suggests that the efficiency of the fibrous roots for metabolite translocation to the plant parts in the C-B system was less than in the other two systems. As a result, sugar beets in the C-B system required more roots than the O-Be-B or C-Be-Be-B systems (significant at a probability level of 10%) in order to produce a unit weight of yield or RWS. The C-B system used 32% and 34% more roots than the O-Be-B system to give the same unit of yield or RWS. When compared with C-Be-Be-B, the C-B system needed 38 and 39% more roots per unit of yield and RWS, respectively.

When the ratio between LAI and root area index (RAI) was calculated for each cropping system the results were 3.43, 4.76 and 6.68 for C-B, O-Be-B and C-Be-Be-B systems, respectively. This means that sugar beets from the C-B system were affected more by the factors which controlled plant growth and development. Also, the longer fibrous roots in the C-B system would consume a large percentage of the photosynthates which could reduce the final crop yield.

3.4.3. Optimal Positions For Root Sampling Studies

The changes in the RLD distribution, which influence plant growth and development, could have been affected by changes in the soil bulk density and its moisture content with depth (Table 26).

Simple correlations between RLD and moisture content (r = -0.581) and between RLD and BD (r = -0.699) were significant for sampling positions 19 and 21, respectively. (Figure 21). Consequently, LAI, TLWR and yield of sugar beets were correlated with RLD at different sampling positions for RLD measurements (Figure 21 and Table 31).

The taproot-leaf weight ratio was positively correlated with RLD except at positions 9, 11 and 16 where the correlations were negative. However, the only significant correlation was at position 5. This means that in studying the role of sugar beet fibrous roots in modifying TLWR, the sampling position for roots is not critical.

Negative correlations between RLD and LAI were found at all sampling positions for the RLD determinations. This indicates that greater root growth would probably dissipate metabolites which could otherwise increase the photosynthetic area (Russell, 1977). More significant correlations occurred at positions away from the main root axis. The area of those positions were between two sugar beet rows where the soil was not disturbed by the tire tracks. This means that the soil physical conditions probably permitted more root growth in that direction. Therefore, the flow of metabolites would be directed towards the roots. Consequently, less metabolite would be available to the leaves and hence LAI would be reduced.

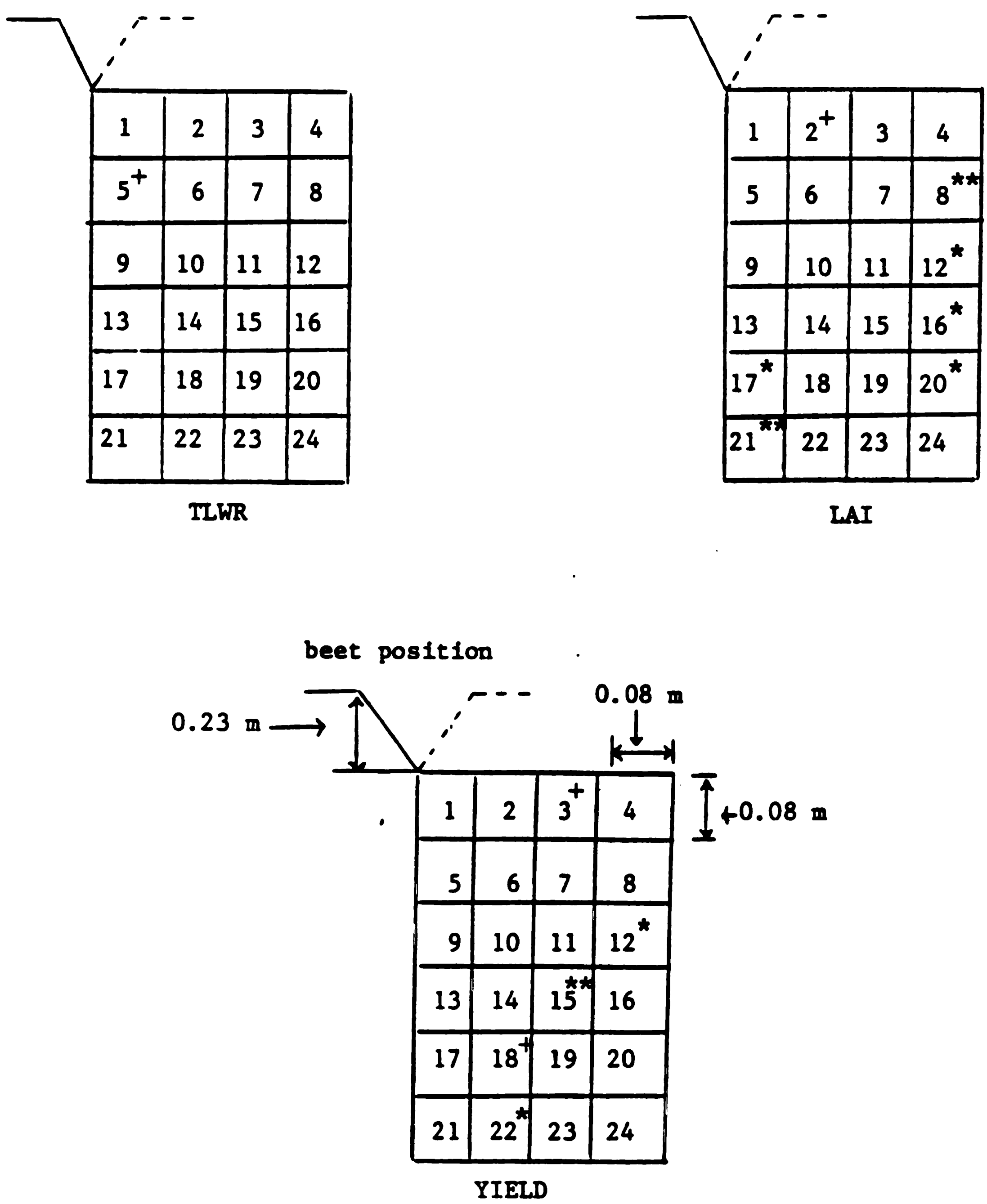


Figure 21. Sampling positions for sugar beet RLD measurements beneath the taproot. Significant correlations between RLD and either LAI, TlWR or Yield are indicated at the corresponding sampling positions.

+, *, ** Significant at 0.1, 0.05 and 0.01 probability levels, respectively.

Table 31. Simple correlations among some plant parameters and root length density (RLD) of sugar beets (US H20) sampled on October 1983 at different sampling positions.

Sampling[†] Position	Plant Parameter[‡] LAI	TLWR	Yield
		r	
1	-0.06	0.30	-0.10
2	-0.55[+]	0.23	-0.34
3	-0.43	0.39	-0.52[+]
4	-0.18	0.29	-0.48
5	-0.20	0.54[+]	-0.18
6	-0.37	0.35	-0.12
7	-0.09	0.31	-0.05
8	-0.72**	0.30	-0.37
9	-0.18	-0.11	-0.37
10	-0.34	0.14	-0.40
11	-0.39	-0.06	-0.35
12	-0.70*	0.42	-0.67*
13	-0.50	0.16	-0.40
14	-0.47	0.00	-0.46
15	-0.36	0.12	-0.73**
16	-0.66*	-0.17	-0.34
17	-0.59*	0.28	-0.36
18	-0.45	0.41	-0.56[+]
19	-0.21	0.31	-0.29
20	-0.62*	0.41	-0.40
21	-0.72**	0.12	-0.39
22	-0.43	0.30	-0.58*
23	-0.23	0.17	-0.38
24	-0.13	0.46	-0.04

† See Figure 21

‡ TLWR = Taproot-leaf weight ratio, LAI = leaf area index and Yield = Sugar beet yield

+, *, ** Significant at the 0.1, 0.05 and 0.01 probability levels, respectively.

Although some significant correlations between RLD and LAI occurred at lower depths close to the root axis (positions 17 and 21), it is more convenient to sample roots at shallower depths. Therefore, positions 8 and 12 where significant correlations were also found seem to be suitable for sampling roots.

The negative correlations between sugar beet yield and its RLD at all sampling positions emphasizes the previous findings (sub-section 3.4.2.). Also, the data in Table 32 illustrate that C-B system which had longer net root length per plant than C-Be-Be-B system resulted in lower yield.

As far as the sampling positions for roots and their role in affecting yields are concerned the most significant correlation was found at position 12. less significant correlations occurred above and below this position (positions 3, 14, 17 and 21). This means that sugarbeet yield was affected by roots distributed away from the root axis and at lower depths.

IV. Greenhouse Experiment

The effect of soil structure on root growth was studied under controlled conditions in the greenhouse. After a growth period of 26 days shoot dry weight and root length from each soil core were determined. Dry beans were used as an indicator crop.

Table 32. Influence of cropping system on fibrous root length and yield of sugar beets (US H20) in a cropping systems study sampled in October 1983.

Cropping System †	Net Root Length ‡	Yield
	$m(plant)^{-1}$	$g\ m^{-2}$
C-B	231 a §	5544a
O-Be-B	181 ab	6961a
C-Be-Be-B	163 b	6469a

† C = corn, B = sugar beets, O = oats and Be = navy beans

‡ Root length was measured in $2.39 \times 10^{-2}\ m^3$ soil

§ Means followed by the same letter or letters in a column are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Results from this experiment together with those measured in the field can help in evaluating soil structure modification and its influence on root growth and development.

4.1. Changes in Bulk Density and Root Length With Soil Core Sampling Depth

The simple effect of sampling depth on both soil BD and root length (RL) was significant (Tables 33 and 34, respectively). The lowest BD was measured at the surface soil core (0 to 0.08 m) and then increased with depth. As a result, RL was the longest in the surface soil core and then decreased significantly with depth except between 0.08 to 0.15 and 0.15 to 0.23 m soil depths. Relative to the first depth, RL decreased by 14.7, 24.2, and 37.3% in soil cores from 0.08 to 0.15, 0.15 to 0.23 and 0.23 to 0.31 m depths, respectively.

4.2. Influence of Cropping System on Root Length and Shoot Dry Weight

The simple effect of cropping system on both root length and shoot dry weight was significant (Tables 35 and 36, respectively). The longest root lengths were measured in C-B and C-C-C-B systems which were significantly different from the other systems. Meanwhile, shoot dry

Table 33. Changes in bulk density (BD) with sampling depth of soil cores for the greenhouse experiment.

Sampling Depth	Bulk Density
m	Mg m^{-3}
0-0.08	1.29 a†
0.08-0.15	1.39 b
0.15-0.23	1.43 c
0.23-0.31	1.48 c

† Means followed by the same letter are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 34. Influence of soil core sampling depth for the greenhouse experiment on root length (RL) of navy beans (Seafarer).

Sampling Depth	Root Length[†]
m	m
0-0.08	7.23 a[‡]
0.08-0.15	6.17 b
0.15-0.23	5.48 b
0.23-0.31	4.53 c

† Root length was measured in 1.38×10^{-4} m^3 soil.

‡ Means followed by the same letter are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 35. Cropping system effect on root length (RL) of navy beans (Seafarer) grown in the greenhouse.

Cropping System†	Root Length‡
	m
C-B	6.68 a§
Be-B	5.64 b
O-Be-B	5.22 b
C-C-C-B	6.70 a
C-Be-Be-B	5.61 b
O-A-Be-B	5.28 b

† C = corn, B = sugar beets, Be = navy beans, O = oats and A = alfalfa

‡ Root length was measured in 1.38×10^{-4} m^3 soil.

§ Means followed by the same letter are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

Table 36. Cropping system effect on shoot dry weight of navy beans (Seafarer) grown in the greenhouse.

Cropping System †	Shoot Dry Weight
	g
C-B	0.318 a‡
Be-B	0.294 ab
O-Be-B	0.296 ab
C-C-C-B	0.294 ab
C-Be-Be-B	0.304 a
O-A-Be-B	0.269 b

† C = corn, B = sugar beets, Be = navy beans, O = oats and A = alfalfa

‡ Means followed by the same letter are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

weight was lower in cores from O-A-Be-B system than those from C-B or C-Be-Be-B systems.

The effect of cropping system on the root length required per unit weight of dry shoot was significant (Table 37). The C-B and C-C-C-B systems used about 17 and 22% more roots than the O-Be-B system to produce a unit weight of dry shoot.

4.3 Discussion

The data in Table 33 indicate that soil structure was different from one depth to another as measured by BD. Simple correlations between RL and BD at any depth were not significant, but all the correlations were negative. This means that as BD increased with depth, RL decreased reaching a minimum below the plow layer depth (Table 34) where BD was the highest.

The lower BD at 0 to 0.08 m core samples relative to the other depths reduced the resistance for roots to proliferate and facilitated their growth. Consequently, longer roots were measured at that depth. Moreover, for the first sampling depth, navy bean roots were able to penetrate deeper into the soil core where more roots were visible at the bottom than any other depth.

As the sampling depth increased, more resistance for the penetration of roots (as measured by BD) resulted in a reduction in their lengths. The highest resistance was

Table 37. Effect of cropping system on root length (RL) required per unit weight of dry shoot of navy beans (Seafarer) grown in the greenhouse.

Cropping System †	RL:Shoot Dry Weight
	$m\ (g)^{-1}$
C-B	21.5 ab‡
Be-B	19.0 ab
O-Be-B	17.8 b
C-C-C-B	22.8 a
C-Be-Be-B	18.6 ab
O-A-Be-B	19.8 ab

† C = corn, B = sugar beets, O = oats, Be = navy beans and A = alfalfa.

‡ Means followed by the same letter or letters are not significantly different at a probability level of 5% according to Duncan's Multiple Range Test.

below the plow layer depth (0.23 to 0.31 m) where RL was the lowest. The unfavorable soil structure at this depth prevented the roots from penetrating deeper into the soil core and most of the roots were clustered at the top.

The data in Table 35 indicate that soil cores from cropping systems which had higher percentage of corn (C-B and C-C-C-B) in the system yielded longer roots. It has been indicated previously (section II of the RESULTS AND DISCUSSION) that these systems contained larger MWD and tended to have higher percentage of larger aggregates. Therefore, larger pore sizes could have been increased which probably facilitated root growth. Meanwhile, the other systems contained smaller MWD and higher percentages of small size aggregates which would be accompanied by smaller pores. As a result, root growth and development were hindered in soil cores from Be-B, O-Be-B, C-Be-Be-B and O-A-Be-B systems.

Changes in shoot dry weight among the cropping systems were not consistent with those of RL (Table 36). That is, shoot dry weight was not affected by the per cent of corn in the system as did RL. It seems that the roots were active in translocating the metabolites to the shoots. Also, the short period of growth (26 days) probably was not long enough to impose differentiation in the partition of dry matter between roots and shoots. In the mean time, the significant effect of cropping systems on the ratio of root length to shoot dry weight (Table 37) indicated some changes in plant growth and development. It is suggested that future varieties of navy beans should consider the ratio of root length to shoot weight when selecting for superior varieties.

Simple correlations between shoot dry weight and RLD from the greenhouse experiment (RLD was calculated from RL and soil volume) was positive for all sampling depths. The only significant correlation was at the 0.08 to 0.15 m soil depth ($r = 0.435$), but the positive values for all depths indicate root activity in nutrient translocation.

The data from this experiment substantiate the previous findings presented in Table 29. Even though two different crops were used for the field and greenhouse experiments the results showed that cropping systems with 50% or more corn enhanced root growth and development. Changes in some soil structural indices such as MWD and aggregate distribution at different sizes could be involved in root behavior among the cropping systems.

SUMMARY

The effect of six cropping systems on soil structure and on some plant parameters were studied in the field. Also, a greenhouse experiment was conducted to relate the results of root growth and development as affected by soil structure to those results measured in the field. Changes in soil structure were measured by several indices. They included bulk density, saturated hydraulic conductivity, air porosity, total porosity, mean-weight diameter of soil aggregates and their stability at different size ranges.

All the measured indices were affected by soil depth for all the sampling dates, but mainly within the plow layer depth. However, there were some variations in the magnitude of change in the structural indices among the dates of sampling. The effect of over winter weathering action resulted in a significant increase in bulk density with depth. Consequently, total porosity, air porosity and hydraulic conductivity decreased. In contrast, the second six month period showed a slight decrease in bulk density which was accompanied by an increase in air porosity to nearly the same value as the first sampling date. It seems that the combined physical effect of sugar beet roots and the enhancement of microbial activities by warmer

temperature played significant roles in modifying soil structure during that period.

Significant differences among the cropping systems used were indicated for some structural indices at specific sampling dates. Systems with corn as 50% or more of the rotating crops had larger mean-weight diameters of soil aggregates for the first sampling date. This was probably the result of organic matter return which increased the microbial action in aggregating soil particles. This resulted in lower bulk density and higher total porosity than the other treatments. The good positive correlation found between C/N ratio and mean-weight diameter substantiates the above explanation. Apparently the effect of cropping systems with high percentage of corn on soil structure was confined only to the plow layer depth. That was indicated by the lower bulk density of the C-B and C-C-C-B systems compared with the Be-B system within the plow depth.

Differences in soil structure among the cropping systems disappeared at the second sampling date. The swelling and shrinkage characteristics of the Charity clay soil could have some effect. That is, the freezing and thawing, which occurred before the second sampling date, probably affected the soil structure more than could be detected by the different systems.

Since a sugar beet crop was grown before the third sampling date, the changes in soil structure with depth could be related to the physical effect of taproots and the extensive fibrous roots of sugar beets. Meanwhile, the larger mean-weight diameter of soil aggregates in some systems indicates the persistent effect of the high organic carbon return from systems with a high percent of corn.

The percent of soil aggregates of the larger size range (5 to 0.5 mm in diameter) were higher in the C-B system than in the O-Be-B or C-Be-Be-B systems. Also, during the period of this study the C-B system showed more changes in bulk density and total porosity than the other two systems. This suggests that the action of the physical, chemical and biological factors in modifying soil structure could be more effective in the C-B system than the O-Be-B or C-Be-Be-B systems.

The plant growth parameters measured included leaf area index, taproot-leaf weight ratio and fibrous root length density of sugar beets. Leaf area index was significantly influenced by the different cropping systems. Smaller leaf areas were produced by sugar beets when preceeded by corn while their root length density was high. This indicates that the growth of the fibrous roots was on the expense of the development of the shoots which could affect their functions.

The taproot-leaf weight ratio was also significantly different among the systems. However, since this index included both shoots and roots, its results were not consistent with the other two indices.

The changes in root length density and leaf area index among the systems were reflected on the yield of sugar beets. Although significant differences were not observed, the 1983 yield of sugar beets was the lowest when the previous crop was corn. Apparently the larger soil aggregates in the C-B system resulted in larger pore spaces which facilitated root growth. Consequently, more dry matter accumulated in the fibrous roots which reduced the final crop yield.

In order to facilitate root studies in relation to other plant parameters, different sampling positions for roots were analyzed. The simple correlation studies indicated that sampling positions of roots to study their effect on taproot-leaf weight ratio was not critical. For leaf area index studies, sampling away from the root axis (0.31 m) and at a depth of 0.15 m below the taproot was a satisfactory position. As far as the relation between yield and root distribution studies are concerned a highly significant correlation was found about midways from the root axis and the sampling depth. Probably the resistance for root growth which started at that position due to increasing bulk density played a significant role.

The significant changes in bulk density with depth for the greenhouse experiment were reflected on the shoot dry weights and the root length of navy beans. Also, the effect of the different cropping systems used in this study on those two parameters was significant.

The greenhouse experiment confirmed the results obtained from the field study concerning the cropping system effect on root lengths. That is, the systems which had 50% or more corn showed increased root growth. However, the relationship between shoot and root growth in this experiment was not clear. It may be that the growth period was not long enough to impose the sink-source relationship and the partitioning of dry matter between shoots and roots.

CONCLUSIONS

The field experiment of this study indicated that all the soil structural indices used changed with soil depth. This was demonstrated by increasing bulk density, mean-weight diameter of soil aggregates and their total stability, and decreasing total porosity, saturated hydraulic conductivity and air porosity. It is important to note that those changes were affected by the time of sampling. Due to the swelling and the shrinkage characteristics of the Charity clay soil, freezing and thawing could have some effects on its structural changes.

The cropping systems used proved to have significant effects on the modification of soil structure. The systems with higher percentages of corn (C-B and C-C-C-B) increased the formation and the percentage of the larger size aggregates (5 to 0.5 mm in diameter) 11 years after the initiation of this experiment. As a result, the soil bulk density was lower and the total porosity was higher than the systems which contained higher percentage of the smaller aggregates (<0.5 mm in diameter). However, during the period of this study, the C-B system showed more dynamic changes in soil structure than the O-Be-B and the C-Be-Be-B systems. This suggests that the accumulation of organic matter returned from systems with high percentages of corn over a long period of time was a prerequisite for the stabilization of the larger soil aggregates.

Modification of soil structure by the C-B system seemed to increase the number and/or size of the soil pores. Consequently, the soil resistance to the growth and development of the fibrous roots of sugar beets was not as restrictive as in the other systems. On the other hand, the leaf area index and its ratio with the root area index were smaller in this system which resulted in a lower yield relative to the other systems. This indicates that both soil and plant parameters should be included in studies concerning the modification of soil structure and its effect on crop production.

Generally, cropping systems which contained 50% or more corn had the tendency for soil structure modification. The significance of this modification on crop production will depend among other factors on the soil type, the environmental conditions and on the performance of the plant growth and development parameters.

The fibrous root length distribution within the soil profile was found to be affected by changes in the soil structure due to the different systems used. The fibrous root length density of sugar beets was negatively correlated with the leaf area index and the final crop yield. The optimal sampling position for roots to study their relation to leaf area index found to be at 0.31 m from the plant axis and at a soil depth of 0.15 m below the taproot. For studies concerning the final yield of sugar beets and its relationship to the fibrous roots, it is better to sample the roots about 0.15 m away from the root axis and at a soil depth of 0.31 m below the taproot.

It is recommended that a continuous corn system be added with yearly measurements of the percentage of soil aggregates at different size ranges for all the systems. Based on the above conclusion, it is also recommended that this study be repeated once in 10 years where all the indices will be measured. This should help to resolve the controversy about the beneficial or detrimental effect of corn on soil productivity.

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