THE EFFECTS OF SOIL COMPACTION ON THE PRODUCTION OF PROCESSING VEGETABLES AND FIELD CROPS

A REVIEW

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by

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ABSTRACT

A review is made of effects of soil compaction on processing vegetables and field crops that are grown in Ontario. The relationships between compaction and soil properties are examined, as well as the effect of vehicle traffic, the effect on root growth and distribution, the effect on nutrient availability and uptake, and the growth and yield of crops on compacted soil. Some attention is given to the economic impact of compaction. The processes of compaction measurement and alleviation of compaction are also examined. Areas of research needing further attention are suggested.

INTRODUCTION

The processing crop industry in Ontario is experiencing a rationalization of its growers (Table 1). In recent years the trend to fewer growers on the same land base has increased the reliance on mechanization, using larger equipment to ensure timely planting, harvesting, and delivery of produce to the processors.

Table 1: Comparing Grower Numbers and Acreage for Processing Vegetables in Ontario, 1986 and 1990.

COMMODITY	ACREAGE (MEASURED ACRES)			NUMBER OF GROWERS		
	1986	1990	CHANGE	1986	1990	% CHANGE
Tomatoes	27,256	28,290	3	637	400	-37
Sweet Corn	36,854	36,410	-0.1	348	325	-7
Peas	15,213	23,540	55	350	422	21
Green and Wax Beans	4,586	6,230	36	71	50	-30
Lima Beans	1,038	1,290	24	26	22	-15
Cucumbers	35,737	34,070*	-5	607	417	-33

*(Contracted Tons)

Crop productivity and quality, as well as profit margins dictate strict and narrow windows in which field operations must be performed. In comparison, grain and oilseed crops can remain unharvested in the field much longer with minimum spoilage or yield decline. The pressure of timeliness, combined with adverse weather conditions, can cause field operations to be performed in wet soil conditions, resulting in soil compaction.

Soil compaction is defined as an increase in density and closer packing of solid particles or reduction in porosity. Compaction of agricultural soils can result from natural occurrences, such as heavy rainfall impact, soaking and internal water tension, or the static weight of overlaying soil. Compaction from artificial sources occurs under the weight of tractors and machines.

It is primarily the topsoil that is affected by vehicular traffic. When a tractor is driven on the soil surface, the influence of wheel pressures reaches through the whole topsoil, but, as a rule, rapidly decreases below it. Compaction influences in the topsoil depend mostly on the contact pressure between the wheels and the soil surface. The larger the total load on the wheel, the deeper the compaction effects will penetrate the soil. These effects are strongly affected by the soil water level.

Production of processing crops is primarily on Ontario's best soils that often fall into the Class 1 category. These inherently highly productive, well drained loams allow the widest envelope of opportunity for machinery to operate, and as such are thought to also be less prone to compaction damage by field traffic in marginal conditions.

However, recent compaction research has shown these types of soils are highly susceptible to soil compaction and the damage to be long lasting. In recent years, declining productivity of fields presently producing processing crops has increased the value of neighbouring fields, of like soil and not yet used by processing crop growers, demanding higher rents and purchase prices. There also is evidence of crop yields reaching plateaus regardless of varietal yield improvements.

The concern of growers and government field personnel has prompted the examination of the growing problem of compaction and its effect in Ontario's processing crop industry.

This review of the pertinent literature has demonstrated that very little research has been done on the effect of soil compaction on processing crops specifically. However, a sizeable amount of work has been done on field crops and on soil properties. The knowledge obtained on the effect of compaction on other crops can be extrapolated to a certain extent to understand the effect on the growth and yield of processing crops.

RELATIONSHIPS BETWEEN COMPACTION AND SOIL PROPERTIES

Concepts of good soil structure vary but the generally agreed concept, as described by Goldstein (1990) is as follows:

> Agricultural crops require a supply of both water and oxygen to their roots to maintain good growth. With the exception of a few crops such as rice, this requires a balance between the portion of the soil's pore space occupied by air and that occupied by water. Water is held in soil by its attraction to soil particles. For this reason water tends to occupy thin films around soil particles and the smaller pores leaving the larger pores filled with air. In addition to atmospheric conditions, ie., rainfall, evaporative demand and regional water table, it is the soil's physical characteristics which determine it's tilth or ablilty to grow plants.
>
> Ideally, primary soil particles are clumped into aggregates. Within aggregates the pores are small and tend to retain water, while the larger pores between the aggregates allow for oxygen diffusion into the soil and drainage of excess water from the soil. If soil particles are uniformly closely packed the pores space is limited and

composed of only smaller pores. Such a soil is said to be compact and will not support good crop growth and yields.

Compaction directly affects several physical soil properties. Bulk density increases due to a decrease in the number and volume of large soil pores, which in turn alters aeration, infiltration, and hydraulic conductivity. Soil strength also increases. Although the changes affect a plants growth and yield, the mechanisms by which compaction affects plants is not understood as well as the structural mechanics of the affected soil.

Porosity and Bulk Density

Compaction reduces soil porosity, which is the ratio of pore space, or voids, to solid material in the soil. When compaction stresses exceed the soil strength, it results in a compression of air filled pore space, because the mineral and organic particles and the liquid fraction are essentially incompressible (Kezdi 1969; Hillel 1980). Compaction alters soil pore structure, reducing the number, size and continuity of the pores through which plant roots can grow. The elimination of pore space brings solid soil material closer together, increasing bulk density.

Compaction primarily destroys large diameter pores, made up of biopores (worm or other boring animal channels) and voids between soil aggregates. These large pores, also called macropores, are important for the internal drainage of water through the soil profile. As soil density increases, the number of large and nonregular pores decrease. The number of small pores, rather, initially increase with compaction before decreasing under heavy compaction, under which conditions all pores change.In a study by Tahla et al. (1979), the ratio of fine pores increased from approximately 65% to 80% of the total pore volume after compaction while macropores decreased from 25% to 5% with a relatively small load to the soil.

Soil texture determines the quantiy of macropores. In coarse textured soils, macropores dominate, while the finer the texture, the higher the amount of small pores, or micropores. In large pores smaller particles can be translocated resulting in a decrease of the pore diameter. The degree of translocation depends on the form and volume of these particles. Each deviation of these particles from the spherical form increases the shearing resistance of the soil (Hartge, 1978; by Horn, 1988), and decreases overall porosity of the soil.

Compaction can reorient aggregates against each other. With light loads, the aggregates stop moving when the increased contact area created offsets the applied force. Increasing the contact area between aggregates reduces soil pore volume. Aggregates deform when the force applied is greater than the aggregate shear strength. The degree to which a soil deforms depends upon the force applied, assuming a constant water content. Soil aggregate strength increases inversely to moisture content (Day and Holmgren, 1958).

Growth limiting bulk densities can result from soil compaction, but vary with soil texture. Using an empirical relationship correlating growth limiting bulk densities with the average pore radius, Daddow and Warrington (1983) determined values for soils of different textures. High silt or clay soils had growth limiting bulk densities ranging from 1.45 to 1.40 Mg/m^{-3}, while values for sandy soils were as high as 1.65 to 1.75 Mg/m^{-3}. Before a soil reaches this point of severe compaction, plants already show significant growth reduction.

When considering the effects of texture on compaction of soil, it is important to remember the effects of particle-size density on the measurement of bulk density. Sand particles are normally more dense than silt or clay, and so for the same pore space, a sandy soil will have a higher bulk density (Harris, 1971; Larson et al., 1980).

Aeration

Compaction affects gas diffusion as a function of air filled porosity (Pascoe and Myrold, 1988). Research (Cannell, 1977; Bridge and Rixon, 1976; Barber, 1984) has shown gas diffusion ceases at about 10% air filled porosity (air filled pore volume/total soil volume).

Compaction changes aggregate structure so that as soil dries, diffusion is not as great as that for non-compacted soil (Currie, 1984). The first pores to empty are no longer as efficient at transporting gases because of their distortion from compaction. This leaves more water-filled small pores and reduces diffusion of oxygen and other gases.

This alteration in soil aeration influences microbial and root activity. Aerobic microbial activity decreases with less than about 25% air filled porosity (Linn and Doran, 1984). If microbes are sensitive to lower aeration, reduced nutrient mineralization or losses from denitrification may result in fertility problems.

Relatively few studies have been made examining the microbiological effect of soil compaction. Studying organic matter decomposition, Parr and Reuzer (1962; in Pascoe and Myrold, 1988) found that carbon dioxide evolution at 5% oxygen was about half that at atmospheric oxygen concentrations. At 0.5% oxygen, decomposition was still three times the anaerobic rate. Similarly, Greenwood (1962) suggested that autotrophic nitrifiers were not inhibited at oxygen levels of 2% concentration.

The studies of the microbiological effects of compaction have confirmed that total microbial populations significantly decline under compacted conditions. Additionally, soil enzymes are more sensitive than microbes to compaction (Dyck; in Pascoe and Myrold, 1988). Soil respiration rates are also lower on compacted soil (Pascoe and Myrold, 1988).

In a study by Smeltzer et al. (1986), total fungal populations were lower on compacted plots for two years after compaction, but after five years no difference could be detected. The exception was Fusarium spp., which can be pathogenic to young plants, which increased in population with compaction. The same study found no difference in bacterial populations throughout the study.

Roots are more sensitive to decreased soil aeration, with growth decreasing dramatically at 10% oxygen concentration (Bridge and Rixon, 1976; Barber, 1984). Grable (1971) , reviewing aeration and its effect on plant growth, noted that root elongation was decreased to 70% of maximum with oxygen concentrations of 6%, although some studies had shown little effect at oxygen concentrations as low as 2%. Grable and Siemer (1968) have shown that the rate of root elongation of germinating corn decreased when air porosity dropped to 10 to 12%. Boone et al. (1987) found compaction, when combined with excessive rainfall, drastically lowered oxygen concentrations and in turn reduced corn dry matter production.

Hydraulic Conductivity

By changing the shape, size and continuity of pores, compaction alters the water conductivity of soil. Poor internal drainage can reduce water movement to roots and increase surface water runoff. The results can be reduced plant growth and soil erosion. Sharda (1977) demonstrated that soil water conductivity decreased 80% in silty clay loam soil near saturation after a modest increase in bulk density. This was attributed to the reduction in large pores. Blake et al.(1976) found this effect to be longterm, lasting as long as ten years after compaction, as shown in Table 2. Unsaturated conductivity can also be reduced by compaction (Reicosky et al., 1981, Canarche et al.,1984).

Table 2. Saturated hydraulic conductivity of a Minnesota soil 10 yr. after compaction (Blake et al., 1976)

Depth (in.)	Uncompacted	Compacted
	(in./d)	
4	27 ± 5.2	6 ± 1.2
10	17 ± 3.3	8 ± 1.4
14	9 ± 1.7	5 ± 1.0
18	11 ± 2.0	7 ± 1.3
26	15 ± 2.8	4 ± 0.8

Soil Strength

The ability of soil to bear a given load without compaction, or trafficability, is dependent on soil texture, organic matter content and, primarily, on its moisture content. Shearing resistance refers to the strength of a soil's internal bonds between mineral and organic components and its ability to withstand external forces without breaking these bonds. If these bonds break, the resulting structural deformation reduces soil porosity and increases bulk density. When soil is compacted, the external pressures on soil structure has overcome its shearing resistance. The trafficability of a soil will determine its susceptibility to compaction.

It is well known that soil texture can determine a soil's susceptibility to compaction. Soil of any texture will be compacted to some degree for a given external pressure and soil moisture content (Raghavan et al., 1976). The particle-size distribution of the soil can influence the reduction in porosity caused by compaction. A soil that contains a uniform mixture of sand, silt, and clay, which is called a well-graded soil, will compact to a lower porosity and usually a higher bulk density than a soil that contains particles that are more nearly the same size (Chancellor, 1976). This is because the particles fit better into a tight pack if there is a gradation in size. Soils with a limited size distribution are referred to as poorly-graded soils. In general, moderately coarse textured soils, such as the sandy loams, on which many acres of processing tomatoes are grown in Ontario, are more susceptible to compaction than poorly graded soils (Larson et al., 1980).

The theoretical particle size distribution that is the most compactible consists of 67% sand, 24% silt, and 9% clay, and fits in the sandy loam class (Larson and Allmaras, 1971). This was verified by tests of compaction on soils of different textures. Soils with less sand were less dense and more porous. Soils with swelling clays were generally more resistant to compaction than soils with non-swelling clays (Harris, 1971).

Roughness of the particles themselves also affect soil strength. Rougher soil particles contribute to give soil more resistance to compaction by increasing soil strength. Rougher particles do not 'compact as tightly as smoother particles under the same compactive force (Cruse et al., 1980).

Horn (1988) gives some guidelines for the compressibilty of a soil relating to clay content. The higher the clay content of a given soil, the more the soil can be compressed. Total settlement is smaller for sandy soils and greater for clays. At the same clay content, a soil can be compressed more the smaller the bulk density. At the same bulk density, load and moisture content, soils with higher clay content have a greater resistance to compaction at short times. Higher amounts of organic matter decrease compactibility (Horn, 1988), and increase the strengh of and between the soil aggregates. Less aggregated soils, that is to say less structured soils, are more easily compressed. Increasing clay content of a soil weakens soil aggregates (Horn, 1988).

The shearing resistance of a soil can depend on the kind of clay minerals as well as the amount and kind of exchangeble cations. The cohesive forces between illite, smectite or vermiculite are higher than for kaolinite, but kaolinite can mobilize higher shearing resistance values expressed as the angle of internal friction (Gibson 1953; by Horn, 1988). Increasing valency of the adsorbed cations or higher conentration of these cations also increases soil strength (Horn, 1988). Increasing the amount of organic matter results in an additional increase of shearing resistance, due to organo-mineral bonding, because it increases the angle of internal friction and cohesion.

EFFECT OF VEHICLE TRAFFIC

The processing crop industry, in recent times, has become more mechanized, as fewer growers work larger acreages. The figures in Table 1, demonstrate this trend.

This trend is best illustrated by the mechanization of Ontario's processing tomato industry. The first machine tomato harvester came into Ontario in 1973. The number of tomato harvesters grew rapidly in the late 1970's and now approximately 80% of Ontario's tomato crop is harvested by machine.

The larger heavier equipment that is used in field crop work include: tractors that weigh from 5 to 15 tons (tractors that weigh up to 27 tons are sold for agricultural use), self propelled combines weighing up to 14 tons and that can carry an additional 7 tons of grain, grain wagons that weigh 9 to 40 tons, and liquid manure tankers and large fertilizer spreaders having loaded weights in excess of 18 tons and pressures that can exceed 200 kPa (Erbach, 1986).

In addition to some of the above equipment used for field crop work, the specialized equipment for processing crops include: self propelled pea combines that commonly weigh 19 tons; self propelled tomato harvesters that weigh from 12 tons dry weight, to 15 tons with sorters, fruit, vines and mud; self propelled sweet corn harvesters weighing 12 tons; and self-dumping transport wagons weighing 3 tons that hold up to 9 tons of produce.

Ground Pressure

There are three forces that are exerted by wheels against the soil (Soane et al., 1980): a downward force from a load; a shear stress resulting from the torque about the axle; and vibration of moving parts within the drive train. As any of these forces increase, the degree of compaction increases.

Soil compaction problems are correlated with increases in the weight of farm machinery. Work by Froelich (1934; in Taylor and Gill, 1984) indicated that the pressure at a point below the surface of the soil is a function of the average soil surface pressure (contact pressure) and the area over which that pressure is applied (total load). This was confirmed by Soehne (1953; 1958) and Taylor et al. (1984; 1980). These research results reinforce the value of the use of low ground pressure flotation tires to support heavily loaded vehicles on agricultural soils. However, larger tires may not always reduce the depth to which compaction occurs and they may increase the area affected by shallow compaction.

This recommendation is greatly influenced by the soil water status at the time of wheel traffic, as well as by soil texture and organic matter content. These relationships were established for a number of soils by Gupta et al. (1985). Soil resistance to compaction increases with organic matter content and decreasing moisture. Traffic with low ground pressure wheels on wet soil may cause greater compaction than traffic with high pressure wheels on a drier soil (Hakansson et al., 1988). Also, the pass of a wheel exerting a pressure onto a specific point smaller than previous traffic had exerted on that point may cause no further compaction (Hakansson, 1988; Horn, 1988).

Three factors affect the contact pressure of a vehicle: the load; the tire dimension; and the inflation pressure. Tire ground pressure is equivalent to the addition of inflation pressure plus some increase for carcass stiffness and uneven pressure distribution. For agricultural tractor tires, 2 - 3 psi is typically added for carcass stiffness (Janzen, 1990). Spreading the same weight over a larger contact area decreases the ground pressure. This could be acheived by decreasing the inflation pressure, increasing the tire dimension or increasing the number of tires.

When one or more wheels are used, increasing the distance between them reduces their interaction, giving a greater load spread and lower stress values in the soil. This was found by Carpenter et al. (1985), and subsoil stress was reduced approximately 50% when the load was applied over tandem axles. Tandem axles were also found to be more effective than dual wheels for reducing compaction, because subsoil stress with tandems was less than duals under the same load.

Increasing the area over which the load acts at the same contact pressure, results in compaction of deeper soil layers (Bolling and Sohne 1982; Horn 1981a, 1985b; Burger et al. 1988; Voorhees, 1988). Stress normally decreases with depth, with the greatest stress under the centreline of the wheel, but the larger the contact area, the slower the decrease. Under an infinitely large contact surface the stress would be the same at all depths, but under a small surface it decreases rapidly with depth. The greater the depth, the larger the influence of the total wheel load.

Taylor et al. (1980) also found that attempting to offset a larger load with the use of larger tires while maintaining constant tire pressures always resulted in higher pressures in the soil at depths of 7, 12, and 20 inches.

The reduction of compaction damage by reducing ground contact pressure has its limits, though. At great depth, the stress caused by traffic mainly depends on the axle load, therefore, controlling the load of a vehicle is the most effective method of controlling soil compaction. It has been concluded that depth of compaction increases with axle load and that axle loads should be limited (Hakansson et al., 1988; Soehne, 1951; Eriksson, 1976; Taylor et al., 1980; Carpenter et al., 1985).

Axle Loads

The use of different axle loads and the comparison of their effects on crop yield have been done by several researchers. In 1981 a total of 26 experiments were started in Europe-North America freeze-thaw areas: Finland, Sweden, Norway, Denmark, The Netherlands, Canada, and the United States. Soil was compacted at each of these locations with vehicle loads of 10 tonnes per single axle or 16 tonnes per tandem axle at the beginning of the experiments. Shallow compaction was removed by annual plowing at depths of 25 cm. After initial compaction, loads were limited to 5 Mg per axle to study persistence of one-time high axle-loading of the soil. It was felt that these studies could lead to a recommended restriction of maximum axle loads over a large region of the world (Taylor, 1990).

It has been found that axle loads greater than 6 tonnes may cause subsoil compaction to depths deeper than 40 cm (Hakansson et al., 1987). This subsoil compaction is not alleviated by frost action and may persist for some time. Voorhees et al. (1986), using axle loads of 9 Mg and 18 Mg per axle, reported that the effects of heavy soil compaction persisted in the subsoil after as many as eight years in spite of annual winter soil freezing to depths of 70 to 90 cm. The magnitude of yield reduction was greater for soil with 70% clay than 10% clay content. Similar findings were reported by Hakansson (1985). Presently available results indicate an axle load above 10 tonnes should never be used (Hakansson et al., 1987). Axle loads above this value have increased bulk density to depths of 60 cm (Voorhees, 1986). Otherwise, there is a risk that the traffic will impair soil productivity for decades, or even permanently.

Tracks and Tires

Tracks are an efficient way of spreading the load over a larger surface area and effectively reducing the contact pressure, especially when the bearing capacity of the soil is low. Recent additions of tracks to help drive a tomato harvester in Ontario reduced contact pressure to approximately 12 to 14 psi from a tire contact pressure of 50 psi (A. Fowler, pers. comm.). The addition of tracks also permitted the operation of the harvester in marginal soil conditions that were too wet for operation on conventional tires.

The track laying vehicle has been said to be efficient only when there is a problem of trafficability of the soil (Hakansson et al., 1988). In the review by Hakansson (1988), several researchers had found that tracks seem to be less efficient on soil of good bearing capacity, yet still sensitive to compaction. One reason for this is uneven pressure distribution under the track. Other reasons include the longer duration of load compared to that under wheels, and more vibration may be transmitted to the soil (Cooper and Reaves, 1960). Also, the normal load is usually concentrated under the supporting road wheels (Byrnes et al., 1982).

There is increasing interest in the use of tracked vehicles on agricultural soils. In the first year of a comparison study between tracks and tires and the effects on corn yield (Erbach, 1986) , the yield reduction for track type tractors was 9% less than for wheeled tractors. In a later report (Erbach, 1988), results of the same study showed that corn yielded, on a four year average, 7% better when cultivated with a track-type tractor than with a conventional wheeled tractor. The yield advantage of tracks over four-wheel-drive tractors was 2.1% per pass of the tractor. Emergence in the tractor tracks was 6% better for tracked tractors than wheeled tractors. The type of tractive device had little effect on grain moisture at harvest.

Janzen (1990), reviewing the Erbach study, went on further to demonstrate the use of tracks on harvest equipment, which are often heavier and potentially cause more compaction damage. He also explained the advantages tracked vehicles have in tractive and fuel use efficiency over wheeled vehicles.

Other Parameters of Traffic

Wheel slippage, which is related to shear stress from the torque about the axle, can affect compaction. Ljungars (1977, in Hakansson et al., 1988) reported no effect of slip on compaction. This is contrary to findings by other researchers. Davies et al. (1973; in Hakansson et al., 1988) reported increased compaction with increased slip. Raghavan et al. (1977; 1978) however reported increased compaction with wheel slip within a restricted range of wheel slip of about 20%. When slip increased past this range, compaction from slippage decreased. Horn (1988) indicated soil compaction increased when a vehicle started or stopped moving.

Erbach (1986), assuming typical field operations for the production of soybeans and corn, estimated the areas trafficked at least once during one year of production to be 85% and 82%, respectively. Other researchers, have made estimates that range from 70% of the field area for alfalfa production (Grimes et al., 1978) to four times the field area in the production of small grains and eight times the field area for root crops and vegetables (Hakansson et al., 1988). Such a value given to compaction intensity is of limited value because there is no value given as to the magnitude of the compactive force. Also, some areas of a field may receive no wheel traffic while other areas may be tracked as much as 20 times (Grimes et al., 1978).

In typical machine harvest tomato production in Ontario, as many as 15 trips across the field are made in a season, barring any excessive weed infestations. For most field crops as many as ten trips is common for conventional management. The number of trips over the field can affect the intensity of compaction and several researchers have investigated the effect of this variable.

Raghavan et al. (1976) found an almost linear relationship between bulk density and number of passes up to ten passes. However, Taylor et al. (1982), found that the first pass of a tire is the critical one for a tilled soil. Using three tilled soils and two loads, 75% of the bulk density change and almost 90% of the sinkage measured during four passes of a tire occurred on the first pass.

The extent of soil compaction also depends not only on the number of passes of the tractor, but also on the speed of travel. Karczewski (1978) showed that the bulk density increase beneath a rigid wheel was much greater at 1 km/hr than at 12 km/h. The same level of soil compaction was reached at approximately twice the depth for slow speed than for high speed.

Controlled Traffic

In row crops the concentration of traffic is in the centre of inter-row areas. This is controlled for benefit in the tillage-planting system known as ridge tillage. In the ridge tillage system, all traffic is confined to inter row areas, yet Parsons et al. (1984) showed that a considerable portion of the field may still be tracked.

The rationale for entirely controlled traffic concept was established by Taylor (1981; 1982; 1983). Controlled traffic research was begun three decades ago by several researchers to increase crop yields by eliminationg compaction from the cropping area. While yield increases have been obtained, reduced production costs may be of more benefit. Timeliness of operations, especially harvesting and spraying, made possible by firm, permanent traffic lanes has yet to be fully evaluated but appears very beneficial.

There are many researchers around the world involved in controlled traffic. There is at least one location where work is being done with specifically designed spanning equipment (also called gantries) in the United Kingdom, The Netherlands (Lamers et al., 1986), Israel (Hadas, 1987), the United States (Taylor, 1981; 1982; 1983; 1986; 1987; 1989) and Japan.

Against the advantages controlled traffic has in the prevention of soil compaction is the disadvantage of the need for improved management and machine technologies. Present machinery design and crop rotations in Ontario do not allow wheel traffic to remain in the same lanes from year to year. It is difficult to assemble machinery sets that have compatable wheel spacing. Any conversion of machinery design to accomodate this concept is largely mechanically and economically impractical to the majority of growers.

Additionally, controlled traffic has sometimes given less positive or even negative results because recompaction after plowing has not occured. Therefore, it may not be a universal solution to the compaction problem.

ROOT GROWTH AND DISTRIBUTION

Compaction alters soil pore structure, reducing the number, size and continuity of the pores through which plant roots can grow. This also reduces the space where roots can displace soil material into as they elongate and expand with growth. Soil compaction, then, can affect a plant's ability to extend its roots throughout the soil and, as such, reduce the area of soil a root can utilize to absorb water and nutrients. Factors that limit the root's ability to supply water and nutrients will affect plant growth and yield.

Compaction increases soil strength and bulk density. At higher levels of soil strength, roots are more sensitive to moisture deficits (Davis, 1984). A similar relationship was found for the root length of pea (Eavis, 1969). However, Muneer, et al. (1982) reported that at increased bulk density, soybean root length decreased with increased moisture level. From the literature, it is evident that a change in moisture potential or water content has a much greater effect on root growth in a compacted soil than a loose soil.

Gerard et al.(1987) conducted studies to determine the compound effect of soil moisture, density, clay content, voids, and strength on the root growth of cotton. They found that bulk density, voids, and clay content accounted for 76% of the variability in root growth. Barley and Greacen (1967) indicated that when root growth is not restricted by soil physical properties, such as temperature and aeration, the main physical factor controlling root growth seems to be soil strength, which changes with bulk density and water content (Dechnik et al., 1985; Mirreh et al., 1973).

Voorhees (1975) demonstrated that aeration of pea seedling roots in compacted soil conditions increased root elongation. In the field, Voorhees (1985) found that a 10 to 15% reduction in soil porosity increased root penetration resistance by four times. Steen and Hakansson (1987) showed that root growth and distribution were reduced below compacted soil zones. Tardieu (1988) showed that heavily compacted soil reduces root growth as much as placing a mechanical barrier in the soil, which allowed water movement but not root penetration.

The influence compaction has on rooting depends greatly on the pore size distribution, especially the pores of a greater diameter than the roots (Ehlers, 1975). Wiersum (1957) demonstrated that roots will grow only through pores with diameters greater than the root diameter. These pores are not detected by penetrometer measurements (Groenevelt et al., 1984; Russell et al., 1974). Several studies indicated that larger pores (cracks, macropores and worm channels) will offer easy access for root growth because roots can bypass the adjacent compacted soil and not have to displace soil particles to elongate. However, roots growing in this manner have a weaker root-soil contact area and water absorption capacity is decreased (Tachibana et al., 1983) unless the water supply is satisfactory (Hasegawa et al., 1987).

Soil wetness can affect the rootability of pores smaller than the root diameter. It was observed that in compacted soil some roots were able to widen pore spaces by deforming the space with root expansion (Blackwell et al., 1985; Boone et al., 1985). Such deformation is easier for roots when soil is wet (low soil strength) than when it is dry (high soil strength).

Stypa et al.(1987) indicate that natural, continuous soil pores occur in the field, but are not present in short term laboratory work. However, holes greater than root diameter have been made artificially to simulate pores in the lab (Dexter, 1986c; Pfleger and Werner, 1986). Generally, the percentage of roots entering these pores increased as the diameter and soil density increased.

A special problem of soil compaction in many arable soils is a severely compacted layer below the plow depth. This severely compacted layer, or plow pan, restricts root growth and available water to the plant roots. Taylor and Burnett (1964) and Taylor (1974) reported on the excessive strength of plow pans (in the southern Great Plains, U.S.) when they were dry. Dryness was the main restriction impeding root growth, since the resistance diminished with rain or irrigation. The critical value of soil resistance at which plant roots will not elongate is affected by soil moisture and stage of plant development. Comparison of the values in the literature is quite difficult because of a lack of information on moisture and development status.

Mechanical obstacles located at the bottom of the plow depth cause a reduction of corn root density above and below the plow pan (Tardieu, 1988c). Greater mechanical resistance of the soil in the plow pan resulted in surface accumulation of roots of corn (Boone and Veen, 1982) and affected the vertical and horizontal distribution of roots throughout the entire soil profile.

Roots which are unable to penetrate a compacted layer of soil are deflected to grow horizontally between the loose and the compact layer until they encounter a vertical crack. The percentage of roots growing down cracks decreased strongly with decreasing crack width and increasing angle of incidence between the root and crack (Dexter, 1986a; 1986b).

Whiteley, et al. (1982) indicated that the maximum pressure a root can exert to penetrate soil is limited by its maximum buckling stress of the root tip, when this is less than other maximum growth pressures. This value varies with species.

It was observed by Edwards et al. (1964) that since it is mostly large pores that are destroyed by compaction, the fine roots might be expected to penetrate the soil easier than thicker roots. Such a response does not always occur, since root diameters are as different as species, and may react differently to compacted conditions (Shierlaw and Alston, 1984).

Compaction can restrict the number of lateral roots growing off the main root. Boone and Veen (1982) reported a decrease in the number of laterals with increasing compaction and thus reducing the total length of plant root growth. However, findings with artificial soil conditions suggest an increase in lateral root number (Barley, 1962; Goss, 1977; Schumaker and Smucker, 1981). This may be the result of larger pores being present in artificial conditions, which is not the case in compacted field conditions.

Other studies have observed that increased mechanical impedance caused distortion of the root apex, or root tip, and induced formation of nodal roots and increased lateral branching (Barley, 1962; Boone and Veen, 1982; Goss, 1977; Schumaker and Smucker, 1981). The mechanical restraint also cause the barley root to curve around the restraint, with lateral roots starting on the outside of the curve and root hairs increasing in number on the inside of the curve (Goss, 1977). Another result of said conditions is zigzaggy growth of roots, due to growth conforming structural surfaces (Lipiec, 1988; Taylor, 1974).

In early research, it was thought that root growth was reduced when the pressures outside the root counteracted the normal cell pressure needed for root cell extension growth. However, this explanation was inadequate when it was shown that pressures as low as 20 to 50 kPa, much smaller than turgid cell pressure, sizeably reduced cell growth in a number of species (Goss, 1977; Russell and Goss, 1974). Further discussion and interpretation (Goss and Russell, 1980; Greacen, 1986; Russell and Goss, 1974) showed the complex metabolic processes involved for mechanically impeded root growth.

In coarse textured soils, the significant factor in impeding root growth may result from the rough surface of sand particles(Cruse et al., 1980). The resulting friction between the particles resists particle displacement by the growing root, preventing expansion or elongation. Chaudhary et al. (1985) reported such findings for the root growth of maize. Certainly compaction would intensify this condition by moving particles closer to each other.

Soil texture does determine how intensely compaction restricts root growth. Hemsath and Mazurak (1974) showed that root elongation of sorghum in clay-sand mixtures with relatively low clay content was the highest, but as penetration resistance increased, root elongation in these mixtures decreased more rapidly than in mixtures with higher clay contents. The ability of pea roots to penetrate a resistant clay has been studied by Champion and Barley (1969) and Gerard et al. (1982). The effect of gravels on corn root growth was reported by Babalola and Lal (1977).

Compaction can affect the speed at which a root elongates. Taylor and Ratliff (1969) showed that an increased penetration resistance of 1.9 MPa decreased the speed of peanut root elongation to 50% of the maximum rate (2.7 mm per hour) through loose loamy sand. The same reduction was noted for cotton root with only an increased resistance of 0.72 MPa. Using spring wheat, Collis-George and Yoganathan (1985) showed that increasing shear strength of a fine sand seed bed from 19 to 52 kPa reduced seminal root elongation from 43.5 to 0.2 cm per day.

As the mechanical resistance of soil increases, the amount of photosynthetic energy required to grow and sustain a given length of root increases (Sauerbeck and Helal, 1986). Compaction reduced the oxygen supply to roots, as shown by studies on winter cereals (Blackwell, 1985; Graham et al., 1986) and tomatoes (Rickman et al., 1966) . The lower rate of oxygen diffusion was also reported by Schumaker and Smucker (1981), also indicating that under compaction the roots consumed oxygen at a higher rate. Thus a greater supply of oxygen is required at the root surface to prevent anoxia in compacted conditions.

The growth of roots through compacted conditions usually causes morphological changes, or changes in the root shape from normal (Kays et al., 1974). Growth in such conditions by barley (Lindberg and Pettersson, 1985), and corn (Barley, 1976) was characterized by larger diameter. This change is patterned down to the cell level, whereby the root cells become shorter along the length of the root and wider along the diameter of the root, without changing cell volume (Barley, 1976).

Several researchers (Barley, 1976; Goss and Russell, 1980; Kays et al., 1974) suggested that the response of root growth in compacted conditions was hormone mediated and indicated that ethylene may play a role. Ethylene significantly increased with root impedement. Dawkins (1983) supported this suggestion, using evidence that despite decreased cell length and decreased root length, compaction conditions do not decrease the overall volume of the root cells.

On the suggestion of hormone involvement, the effects of mechanical impedance on root morpholgy and the levels of abscisic acid (AbA) and indol-3-ylacetic acid (IAA) in the root tips of corn (*Zea mays* L.) were studied by Lachno et al.(1982). AbA is thought to act as the root cap, or tip, growth inhibitor and IAA is thought to be the root tip growth hormone. Under impedance, levels of AbA did not differ greatly from that of normal. However, IAA levels increased about 3.5 times higher than normal. It was concluded that this response is likely to be the main cause of the morphological and growth changes brought by impeded root growth conditions.

The influence of mechanical impedance on water uptake by plant roots is not uniform. Agnew and Carrow (1985) reported that compaction of silt loam decreased total water use, but increased water use per gram of roots. However, in other studies (Bar-Yosef and Lambert, 1981) increased bulk density of sandy loam resulted in lower water use efficiency. Lipiec et al. (1988) reported that an increase of bulk density of clay soil resulted in both significantly higher total water use and water use per gram of corn roots grown under soil water tension of 97 or 243 kPa.

The high water use efficiency by roots in compacted soil is attributed to higher unsaturated hydraulic conductivity (Boone et al. 1985; Lipiec et al., 1983) and decreasing percolation losses (Patel and Singh, 1979), but lower water use in compacted soil was related to low oxygen levels (Agnew and Carrow, 1985).

Supplying a crop with adequate water and minerals in the resisted root system in compacted soil depends on rainfall intensity and distribution during the growing season (Wilhelm, et al., 1982). In a dry year, reduced soil water which increases soil strength, may restrict root penetration into deeper layers and thus limit water absorption. In a wet year, mechanical impedance does not restrict root penetration, but if rainfall is excessive, insufficient aeration may cause reduction of water absorption. Mild stress conditions affect yields of plants with a resisted root system more than unresisted ones (Taylor, 1971).

COMPACTION EFFECTS ON NUTRIENT AVAILABILITY AND UPTAKE

A plant receives its nutrients at its roots by a combination of root interception, mass flow, and diffusion. The process of diffusion supplies most of the phosphorous and potassium to the root. Nitrogen, on the other hand, is supplied by mass flow. Compaction reduces mass flow through large pores, which could reduce nitrate flow to the plant roots. Phosphate and potassium availability could be affected by the reduction in root extension caused by compaction, which results in a smaller soil volume explored by roots.

In a study by Castillo et al. (1982), the decreased volume of compacted loamy soil (to 1.30 Mg/m^{-3}) explored by pea roots (*Pisum sativum* L. cv. Alaska) resulted in reduced Ca, K, Mg, and Mn uptake, while there was no significant effect on B, Fe, and P uptake. It was also reported that a considerable proportion of the root system situated in the upper layer of compacted soil did not participate in ion uptake (Verpraskas and Miner, 1986).

Surface accumulation of roots resulting from the mechanical impedance of a hardpan layer in the soil profile can develop an uneven distribution of nutrients and even give rise to nutrient exhaustion of the surface layers (Boone and Veen, 1982).

Decreases in the concentration of nutrients in a crop due to reductions of the rooting zone because of compaction were reported by several authors (Bolton et al., 1979; Ide et al., 1982). However, the uptake of phosphorous and potassium, expressed as units per root length unit, increased in corn, wheat, cotton, and groundnut roots with increasing resistance (Bennie and Burger, 1983).

In artificial soil conditions, consisting of a bed of glass beads, the effect of compaction on nutrient uptake was studied (Lindberg and Petterson, 1985). As pressure on the glass beads was applied, the concentration of nitrogen and calcium in the roots and shoots decreased. The largest effect was on calcium uptake. Compacted conditions had little affect on the uptake of potassium and sulphur. Russell and Goss (1974) observed a similar effect for phosphorous, as well as potassium in a different study.

Lower nutrient uptake on compacted soil may be compensated by higher absorption by roots outside the compacted area in favourable conditions and thus total nutrients need not be decreased. This was shown by Kubota and Williams (1967) for globe beet and barley, and yet crop yields were still reduced.

It also has been suggested (Peterson and Barber, 1981) that the shorter, wider root cells resulting from compaction induced root growth would have greater adsorptive surface area and this would help in overcoming nutrient stress when roots are grown in compacted conditions.

Higher cation exchange capacity of roots (RCEC) of eight plants, including sunflower, pea, corn, soybean and lentil, resulted from increasing the bulk density of clay loam from 1.1 to 1.8 Mg/m^{-3} (Kalkarni and Savant, 1984). This effect was apparently due to an increase in the percent of N and -COOH groups in the root. Root xylem accumulations of toxic anaerobic metabolites also increase with bulk density and are inversely related to the oxygen diffusion rate in the soil (Asady et al., 1985).

The influence of mechanical resistance on ion uptake depends on the nutritional level of the soil. The effects of compaction in highly fertile soils are primarily due to changes in moisture and aeration In soils of low fertility, a slight reduction in root elongation can reduce uptake of immobile nutrients (Byrnes et al., 1982).

In a study by Boon and Veen (1982), with a high phosphate supply in sandy loam, the uptake of N, P, and K per unit of root length of maize was independent of mechanical resistance, suggesting that the rate of ion uptake is related to root length. Other papers suggest that soil compaction increases the movement of ions towards the root by diffusion (Kemper et al., 1971; Philips and Brown, 1965), but decrease the amounts of nutrients mineralized from soil organic matter. This reaction depends on the kind of elements and the way in which they are absorbed.

As a result, crops grown on compacted soil often show symptoms of nutrient deficiency. This condition may be the result of two factors (Byrnes et al., 1982). Denitrification resulting from ponded water on compacted soil can reduce available nitrogen; and reduced root exploration combined with reduced water movement results in less available nutrients. This deficiency occurs even though the total soil supply could be adequate under uncompacted conditions.

Nitrogen

The absorption of nitrate occurs by mass flow and its rate of absorption depends on quantity. Since compaction reduces the porosity and aeration of the soil, the reduction of these two properties could affect soil nitrogen availability. Reductions in mass flow mean smaller amounts of nitrogen being delivered to the root surface. Also, compaction increases the potential for denitrification and subsequent nitrogen losses, given that anaerobic bacteria flourish under the wetter conditions.

A reduction in nitrogen uptake by corn was reported by Voorhees (1985) after the soil was compacted by a 20 ton vehicle, and substantial yield reduction resulted. Other studies report soil nitrogen levels were reduced by compaction (Copeland, 1957; Grable and Siemer, 1968; Blackwell et al., 1986). Other studies have demonstrated the importance of placement of nitrogen for optimum root utilization in compacted conditions (Garcia et al. 1988; Chauhary and Prihar, 1974).

The influence of controlled wheel traffic on soybean nitrogen fixation was reported by Lindeman et al.(1982) and Voorhees (1975). The experiments showed that compaction reduced nodulation and effective nitrogen fixation in wet years, while improving them in dry years.

Phosphorous

Phosphate is absorbed by diffusion. Its absorption is strongly dependent on the size of the root system, unless the phosphate uptake per unit length of root increases with decreased growth.

Studies have shown that soil compaction reduces the uptake of immobile phosphorous, more than other nutrients (Boone and Veen, 1982; Khanna, 1974; Parrish, 1971; Prummel, 1975; Shierlaw and Alston, 1984; Mu'azu and Skopp, 1986) . Shierlaw and Alston (1984) showed that bulk density affected phosphorous uptake of ryegrass but not corn. The corn roots increased uptake of phosphorous from roots in noncompacted layers in the soil profile to compensate for reduced uptake in compacted layers. Parish (1971) demonstrated that a lower uptake rate of phosphorous than other nutrients resulted in an increased nitrogen/phosphorous ratio in the plant.

Potassium

Potassium, like phosphorous, is absorbed by diffusion and its absorption is also dependent on the size of the root system.

Compaction generally results in lower plant potassium levels. Increases in soil bulk density reduce potassium levels in plant top growth. Bulk density increases raised potassium uptake per root unit length, but the decrease in root growth reduced plant uptake overall (Hallmark and Barber, 1981; Sillberbush et al., 1983). Work with corn seedlings demonstrated reduced soil aeration results in reduced potassium uptake by roots (Lawton, 1945; Danielson and Russell, 1957) .

There is a problem in isolating the cause of decreased potassium uptake in compacted conditions. Sections of the plant root that have more potassium available will compensate for sections that are potassium starved (Coale and Grove, 1986), but overall potassium levels will still be lower than if overall potassium was adequate (Claasen and Barber, 1977). It has been speculated that soybeans move more soil solution to the root surface to accumulate more potassium when under potassium stress, causing higher transpirational losses (Coale and Grove, 1986).

Other studies demonstrate increases of potassium are attributed to increased available soil moisture; decreases are attributed to poor aeration from an excess of soil moisture (Estes, 1972; Hargrove, 1985; Triplett and Van Doran, 1969; Bower et al., 1945; Lawton, 1945).

GROWTH AND YIELD OF CROPS ON COMPACTED SOILS

After reviewing the literature, it is obvious that most of the research on soil compaction has been focused on field crops rather than processing vegetable crops. Certainly, this suggests that there is much work that needs to be done in the future in the processing crop area.

After reviewing the literature, the effects of compaction on yields do indicate general trends on the growth and yield of processing crops that are also evident from the work on field crops. Compaction can reduce yield by reducing the quality, weight, and size of fruit. It will delay plant development and thus delay maturity of the crop. Surface compaction can reduce the stand of seedlings and seedling emergence with the formation of a surface crust. Plant height will be reduced by higher soil density. However, a plant that has all of its needs met will not suffer from the compacted soil it is growing in. Additionally, in dry weather conditions especially, moderate compaction can improve yields by improving seed to soil and root to soil contact, thereby improving soil water and nutrient availability to the plant root. In addition to direct effects on yield, subsoil compaction can also reduce yields by delaying planting and other field operations.

Research studies from Minnesota, Sweden, and Quebec (Voorhees, 1987; Hakansson, 1985; Raghavan et al., 1979; Gameda et al., 1987) show that the effect of severe subsoil compaction on yields generally diminishes with time. A onetime compaction with axle loads of 10 tons or greater show a similar trend of initial lower yields. However, yields on that compacted soil approach the yields on uncompacted soil after two to seven years, depending on the soil and climate, and given that the heavy axle loads are kept off the area after initial compaction. Slower recovery of yields generally occured on soils higher in clay (Voorhees, 1987).

In the literature, compacted soil conditions reduced the root size of potatoes, peas, winter rape, oil radish (Petelkau et al., 1985), winter wheat (Barraclough and Weir, 1988; Masse et al., 1988; Petelkau et al., 1985; Trouse, 1979), corn (Bennie et al., 1988; Boone and Veen, 1982; Kayambo and Lal, 1986; Sauerbeck and Helal, 1986; Shierlaw and Alston, 1984), sorghum (Hemsath and Mazurak, 1974), timothy (Gaheen and Njos, 1978), spring barley (Lipiec et al., 1990; Lipiec and Tarkiewisz, 1990; Petelkau et al., 1985), spring oats (Lipiec et al., 1990; Petelkau et al., 1985), winter rye (Lipiec et al., 1990; Trouse, 1979), winter barley (Willat, 1986), field bean (Kahnt et al., 1986) and soybean (Kahnt et al., 1986; Kubota et al., 1983; Muneer et al., 1982).

In most cases, roots encountering mechanical impedance increase their diameter. Higher mechanical impedance resulted in thicker roots of potatoes (Boone et al., 1985), corn (Boone et al.,1986; Boone and Veen, 1982; Logsdon et al., 1987b; Shierlaw and Alston, 1984; Veen and Boone, 1981), pea (Castillo et al., 1982), bean and soybean (Kahnt et al., 1986), and wheat (Collis-George and Yoganathan, 1985a) .

Compacted subsoils can also restrict the root growth of orchard crops, restricting the area explored by tree roots and ultimately affecting yield and tree life (Perry, 1984).

Processing Vegetable Crops

Tomato root penetration, vine growth, and marketable fruit yield were reduced when a Geary silt loam soil was compacted to a density of 1.7 g/cm^{-3} (Greig et al., 1964). Tomato response was not affected by less severe compaction levels.

Two studies on tomatoes demonstrated the importance of soil moisture in compacted soil. In the first study (Flocker and Nielsen, 1962), results showed that increasing bulk density alone did not affect tomato yields. The level of bulk density affected tomato growth and yield only at high soil suctions, when soil strength increased sufficiently to impede root growth. The second study (Flocker and Nielsen, 1960) concluded that nutrient absorption of tomatoes was not directly related to soil density. Again, the growth was restricted in higher bulk densities by an insufficient rate of water available for normal growth.

Wittsell and Hobbs (1965) showed that increasing the bulk density of a silt loam soil in Kansas from 1.2 to 1.7 g/cm^{-3} delayed ripening two weeks and cut yields by 58%.

Karlen, et al, (1983) demonstrated that excessive soil moisture, which also causes low soil aeration, promotes a non-bacterial "soft fruit" condition which reduces the storage quality of tomatoes. Soil compaction, as discussed earlier, reduces soil porosity, and results in reduced internal water drainage and excessive soil moisture.

Rumsey, et al, 1989 working with a corn - tomato rotation on raised beds showed signifantly reduced compaction both in the furrow and in the centre of the bed for reduced tillage compared with conventional tillage. However, there was no significant difference in tomato fruit quality or yield, and it was suggested this non-effect was a result of irrigation trials combined with the tillage comparison.

Pea yields have been shown to be inversely related to bulk density. Yield reductions were attributed to stand reduction and reduced yield per plant in research by Hebblethwaite and McGowan (1980). When compacted dry, bulk density of the light gravelly loam increased from 1.40 Mg/$^{-3}$ to 1.66 Mg/m^{-3}, and to 1.71 Mg/m^{-3} when compacted wet. Dry compaction reduced yields 17% to 39% and 51% to 55% when the soil was compacted while wet.

The impact compaction has on the common root rot of peas, caused by *Aphanomyces euteiches*, has been studied in Minnesota by Percich et al. (1989). The conclusions include the following:

a. Soil compaction reduced pea growth beginning at the 2 -3 node stage and continued through the peak bloom,

b. Aphomyces root rot severity appeared to be enhanced in compacted rather than non-compacted soil, and

c. Soil compaction increased water logging and decreased internal drainage.

This study could serve as a model for studies of other soil-borne fungal pathogens such as *Fusarium*, *Pythium*, *Phytopthora*, and *Rhizoctonia* species.

Two other studies with peas (Smucker and Erickson, 1987, Allmaras et al., 1986) indicated that anaerobic conditions, that could be enhanced by soil compaction, increase the incidence and severity of *Fusarium* root rot.

In another study, Sumner et al. (1976) showed that the incidence of the root diseases of Southern Pea, *Rhizoctonia solani* and *Ceratobasidium* spp., increased with soil density.

In the study by Flocker et al. (1966), sweet corn yield was unaffected by compaction of a Yolo loam to a density of 1.8 g/cm^{-3}.

The yield of cucumbers after soil com^{p}action was studied in Georgia by Smittle and Williamson (1978). An interaction of seed grade, nitrogen source and seedbed compaction was found. A prior study (Smittle and Williamson, 1977) showed that compaction reduced tissue concentration of nitrate by 50%, caused a 25% to 35% yield reduction and decreased the fruit length/diameter ratio. Root growth of cucumber was reduced by soil strength less than 500 kPa, and was reduced 80% at a soil strength of 850 kPa.

With carrots, a characteristic morphological response to mechanical impedance to root growth is forking and fanging (White, 1978).

In a field experiment with potatoes (van Loon and Bouma, 1978) compacted topsoil retarded vertical root growth. This resulted in the lack of significant capillary transport through dense soil between the groundwater and the lower boundary of the root zone, which contributed to significant yield losses.

The effects of soil compaction on potato yield and quality were studied by Flocker and Timm (1964) and showed compaction reduced plant emergence, growth rates, and increased incidence of mishapen tubers. Yield was reduced 51% to 71% over the two year study.

The marketable yield of 'Dixie' squash (*Cucurbita maxima* Duch.) was reduced by 46% to 58% by increased soil strength due to wheel traffic (Smittle and Williamson, 1977). Plant and root growth and root distribution were also reduced.

The root growth of lettuce is affected by small increases in soil bulk density (Carr and Dodds, 1983). Increasing the bulk density from 1.25 Mg/m^{-3} to 1.50 Mg/m^{-3} of a structureless sandy loam reduced plant fresh and dry weight by 25% as well as affecting the rooting pattern.

Soil compaction reduced emergence and stand of pinto bean plants and increased incidence of Fusarium root rot (Croissant et al., 1988).

Reeder (1990) reports on continuing research with tomatoes, sweet corn and cabbage using 10 tons and 17 tons per axle to compact plots at The Ohio State University. The results from the first year after compaction is shown in Table 3. Results for 1990 were unavailable at the time of writing the review. It is interesting to note, however, early indications were that the compaction from 1989 was going to affect crop yields to a greater extent in 1990 than in the first year of the study. Tomato and cabbage top growth was visibly reduced, with the reduction proportional to the level of compaction. Compaction had also delayed plant development. With the heavier compaction of 17 tons, cabbage head development was severely inhibited.

Field Crops

Most of the research done on the growth and yield of field crops on compacted soils has been with corn, soybeans, wheat and barley. The yield data is summarized in Table 3.

In a study selecting dry bean lines in Michigan (Ghaderi et al., 1984), soil compaction reduced yield, pods per plant, and seeds per pod. Another (Mulligan et al., 1985) concluded that soil compaction caused a decline in the symbiotic colonization of dry edible bean root systems by VAM (vesicular arbuscular mycorrhizal) fungi.

Combined surface and subsoil compaction reduced corn yields an average of 14.5% compared to a reduction of 7.5% with surface compaction alone on a Waukegan silt loam in Minnesota (Adams et al., 1960). In another study in Minnesota (Voorhees, 1987), compaction of a Webster clay loam using 10 and 20 ton axle loads reduced corn yields to 155 bu/acre and 125 bu/acre, respectively, from 170 bu/acre on the non-compacted soil.

A one time heavy compaction was shown to affect corn yields in Quebec for several years (Gameda et al., 1987). Reductions of 23 to 25% for three years after compaction on clay soil resulted from compaction with 10 and 20 ton loads.

Corn root length sharply decreases with increased bulk density. Shierlaw and Alston (1984) demonstrated this by increasing bulk density from 1.20 to 1.75 Mg per cubic metre. Bulk densities in clay loam of 1.25, 1.35, and 1.45 Mg per cubic metre reduced the daily root elongation rate by 57, 67 and 72%, respectively (Trouse, 1979).

However, Stypa (1987) reported that corn root growth in the field was not reduced by high subsoil bulk density and suggested that natural cracks and biopores permitted root development without restriction.

Martin et al. (1985) reported compaction increased trifluralin injury to corn seedlings and delayed seedling emergence by a day.

Lindemann et al. (1982) evaluated the effect on soybean yields by compacting a clay loam with up to three passes of a 3583 kg tractor. In dry years, yields were improved by up to 15%, and decreased as much as 6% in wet years. However, the effect of compaction was not statistically significant and appeared to be dependent on the amount of precipitation in the growing season.

Another study using soybeans (Katoch et al., 1983) found that increasing the bulk density of a silty clay loam from 1.14 Mg/m^{-3} to 1.53 Mg/m^{-3} significantly decreased nodulation, yield, and protein content. Grain yield and protein content were 77% and 88% of the soybeans grown on the non-compacted soil.

Studies in a field experiment on silty clay loam (Voorhees et al., 1976) also showed that compaction can affect soybean root nodulation. Soybean rows with wheel traffic on both sides had 20% to 30% fewer nodules and about 36% less total nodule mass than rows with wheel traffic on one side only.

The incidence of *Phytoptora* root rot of soybeans increases in fine textured soils subjected to compaction (Fulton et al., 1961; Gray and Pope, 1986).

Compaction can also reduce the emergence of soybean seedlings by up to 65% (Saini and Singh, 1980). Soybean hypocotyl growth was found to be significatly affected by soil resistance and was quantified by Knittle et al. (1979).

Work in Michigan using Corsoy soybeans (Smucker, 1985) demonstrated that compaction reduced root growth and plant nitrogen levels, but did not reduce crop yield.

Reeder (1990) reported on ongoing work done by The Ohio State University for corn and soybeans, using 10 ton and 20 ton axle loads. These and other results are summarized in Table 3.

TABLE 3. Effect of soil compaction on crop yield.

CROP	LOAD (tonnes)	PRESSURE (kPa)	TIME (Years)	YIELD EFFECT (% Change)	REFERENCE
Tomatoes				-80	Flocker and Neilsen (1960)
				-58	Wittsell and Hobbs (1964)
	9		1	-10	
	15.5		1	-5	Reeder (1990)
Pea				-83,-61 dry	
				-49,-45 wet	Hebblethwaite and McGowan (1980)
Sweet Corn	9		1	-35	
	15.5		1	-48	Reeder (1990)
Potatoes				-51 to -71	Flocker and Timm (1964)
	2.0		1	-35	Voorhees (1977)
			1	-12 to -50	van Loon and Bouma (1978)
				-54	Swan et al.(1987)
				-21	Swan et al.(1987)
				-35	Swan et al.(1987)
				-15	Swan et al.(1987)
		-10		+1	Rychnovsky (1985)
Cucumber	2.1		1	-50	Smittle and Williamson (1978)
	2.3		1	-25 to -35	Smittle and Williamson (1977)
Cabbage (early)	9		1	-85	
	15.5		1	-45	
(late)	9		1	-49	
	15.5		1	-27	Reeder (1990)
Squash	2.3		1	-46 to -58	Smittle and Williamson (1977)
Lettuce				-25	Carr and Dodds (1983) Field Beans
Field Beans (*Vicia faba*,	3.0 cv. Maris)			-26	Brereton et al. (1986)
Pinto Beans	3.4	1216	1	-18	Croissant et al. (1987)
	2.7		3	-40	Schwartz et al.(1990)

TABLE 3 (continued). Effect of soil compaction on crop yield.

CROP	LOAD (tonnes)	PRESSURE (kPa)	TIME (Years)	YIELD EFFECT (% Change)	REFERENCE
Corn	8.1	150	3	-8 to +8	Bicki et al.(1990)
		240	3	-15	Mielke and Jones (1990)
	9		1	+5 to +10	
	18		1	-5	Reeder (1990)
	2.7	180	1	-7	Nelson and Roberts
	9		1	-10	Voorhees (1987)
	18		1	-27	Voorhees (1987)
	5.4		2	-7.5	Swan et al.(1987)
				-16 to -2	Boone et al (1987)
			1	-11	Erbach (1986)
	11.3		4	-43 to 0	Lowery and Schuler (in press)
	20		1	-50	Raghaven et al. (1978)
	2.3			-14.5	Adams et al. (1960)
	3.6			-7	Adams et al.(1960)
Soybeans	8.1	150	3	-8 to +8	Bicki et al.(1990)
	9		2	-6	
	18		2	-6 to -28	Reeder (1990)
			15	-20 to +15	Swan et al. (1987)
	9 & 18		11	-55 to +5	Voorhees et al. (1985)
			1	-23	Katoch et al. (1983)
			1-	-10 to -50	Stucky (1982)
	1.8		6	-6 to +15	Lindemann (1982)
Edible Dry	Beans			-15	Gaderi et al.(1984)
Wheat	9 & 18		3	-55 to +5	Voorhees et al.(1985)
	4.2		3	-30 to +50	Swan et al. (1987)
				-20 to -6	Riley (1988)
Oats				-38 to +17	Butorac (1982)
Rye				-22 to -10	Butorac (1982)

ECONOMIC LOSSES FROM COMPACTION

The economic cost of soil compaction, although difficult to quantify, has been estimated by several sources (Gill, 1971; Hakansson et al., 1988). A recent estimation by the Ontario Ministry of Agriculture and Food estimates the cost of compaction and erosion to Ontario farmers to be in the 70 million dollar range (McBride et al., 1988).

Most obvious of all losses is the loss from yield reduction. The reduction in productivity is a direct reduction in income to growers.

Let's examine a hypothetical situation that could occur if soil compaction was reduced. One can assume that demand for processing crops is fairly constant and production levels are set by processors based on estimates of consumer demand. Using estimated yield levels per hectare of land, the processor can determine how big a land base is necessary to produce the amount required to meet consumer demand.

Hypothetically, the full value of an increase in productivity, if soil compaction damage was suddenly or gradually removed, would be a benefit to growers. With increased productivity per hectare of land, processors would decrease the size of land base needed to produce the crops for the same given consumer demand. Let's assume that grower input costs are relatively fixed to provide one hectare of crop production. With increase yields and decreased land base, the grower would now be delivering the same amount to the processor using less area of his farm to produce that amount. The profit margin per hectare of land will have increased, but the number of hectares in production will have decreased, so that income from a particular crop to a given grower will have stayed the same. The benefit to the grower comes to him in one of two ways in this hypothetical situation. He will either benefit by being able to grow additional acres of another profitable crop on his land where he once accomodated a larger area of the first processing crop, or the higher margins in the processing crop may turn a crop with a net loss to one that turns a net profit.

In an another situation, higher productivity per hectare, combined with an expanding demand market could maintain the existing land base. In this case, the grower would realize bigger margins on the same amount of land and benefit directly from yield increases. Processors would benefit from improving economy of scale.

However, this situation assumes a constant price per unit and does not take into account the complexities of production contracts that affect crop unit price and production levels.

In addition to direct effects on yield, subsoil compaction can also reduce yields indirectly. Slow internal soil drainage caused by compaction can prolong wet soil conditions, delaying field operations that enhance yield. Planting past the optimum planting date for maximum yields can result in reduced yield. Other field operations that enhance yield could include timely spraying and harvesting.

Crop quality is reduced by soil compaction. Any reduction in quality that reduces the unit price of a commodity is a direct reduction of income to the grower and a potential problem in product standards for the processor, which in turn may have to use the lower quality produce in lower value product. Quality reductions may affect size, shape or chemical composition. Quality is reduced by retarded plant growth that results in improper or delayed development of the crop due to soil compaction.

Compaction can affect economic loss by increasing grower input costs. Draught requirements for tillage operations may be drastically increased by soil compaction. Voorhees (1979) reported a 43% draught increase to plough a clay loam soil that had been previously compacted by five passes of a 7 tonne tractor. Compacting the soil with just one pass resulted in a 25% increase in draught. To counteract the negative effects of compaction, more fertilizers and fungicides may be used. All this translates into higer input costs for growers, but probably not as large as reduced yields.

When compaction impairs water infiltration, and reduces soil water holding capacity, it increases the amount of surface runoff and erosion. There is economic loss when topsoil is lost due to erosion. Crop nutrients and soil productivity are washed away, in addition to potential environmental concerns over the effect on waterways.

Offsetting the reductions in productivity from soil compaction are the advantages of efficiencies of machine size and timeliness of field operations. Harvesting at the optimum time regardless of soil conditibns can bring short term economic benefit when the yield and quality of a high value crop would decline if left in the field. In this way, income is increased. Additionally, a bigger machine can cover more area at a faster pace and do so with less labour. The use of heavy hauling equipment, such as grain carts, to transport produce to and from the harvesting equipment also increases efficiency. This reduces production costs.

It has been argued, for grain corn, that the expenses of compaction are covered by the improvements in efficiency and increased crop quality and yield due to timely harvesting (Stephens, 1990). However, there are arguments that support the opposite.

Under Scandinavian conditions (Hakansson et al., 1988), results of experiments show that soil-damage-costs caused by heavy machines are often as high as the machinery and labour costs.

Hakansson (1985a) calculated the penalty for soil damage from spreading liquid manure with a heavy tanker on wet soil in early spring to be $30 - $300 per hectare. This would vary with soil, crop and machinery variables, but under the worst conditions, this cost exceeds the value of the nutrients found in the manure.

ALLEVIATION OF COMPACTION

Natural processes

Natural processes, such as freezing and thawing (Horn, 1985; Groenevelt, 1991), or wetting and drying can do much to alleviate compacted soil. In a study by Voorhees (1983), natural processes reduced penetrometer resistance in the tilled layer of soil by 50%. The forces involved with soil freezing and ice lense formation are enormous (Groenevelt, 1990). Its extent depends on the moisture level in the soil, as well as outside air temperature and snow cover. Frost action is more apparent when the soil is wetter at the time of freeze-up (Voorhees, 1983). Wetting/drying cycles are only active in swelling clays so their effect is dependent on soil type. Additionally, the alleviation of compaction from natural processes is limited to the upper levels of the soil profiles, in which freezing and drying are most likely to occur. The result is that there is alleviation of compaction in the surface layers, but alleviation in the subsoil takes much longer.

Voorhees et al. (1986), using axle loads of 9 Mg and 18 Mg per axle, reported that the effects of heavy soil compaction persisted in the subsoil after as many as eight years, in spite of annual winter soil freezing, to depths of 70 to 90 cm (Minnesota). The magnitude of yield reduction was greater for soil with 70% clay than 10% clay content. Similar findings were reported from Sweden by Hakansson (1985) and Gameda et al. (1987).

Bullock et al. (1985) demonstrated that the natural regeneration of porosity in the top 5 cm of compacted silty clay loam soil occured after 18 months. The soil below that depth remained compacted for a longer period of time. Compaction had decreased porosity to less than half. Aura (1983), however, found that the porosity of even the most severely compacted silty clay soils was alleviated from one spring to the next.

Other studies, Thorud and Frissell (1969) and Pollard and Webster (1978), also have shown that natural alleviation was limited to the surface 8 to 10 cm, after 9 and 6 years, respectively.

Heinonen (1986) suggested that one intensive cycle of drying and wetting may be enough to eliminate deep compaction in vertisols, but that in sandy subsoils compaction may be permanent, unless the soils are mechanically or biologically loosened.

Effects of compaction are usually less permanent in clay soils than in medium and coarse textured soils. Compaction can be alleviated by the shrinking and swelling forces associated with wetting and drying cycles of clay soils. Some soils may alleviate compaction in a few days, others take months. Meredith and Patrick (1961) studied the root penetration of Sudan grass into the subsoil of two soils: swelling clay loam and non-swelling silty loam. Their findings show compaction is more likely to occur in non-swelling soils. This conclusion is seconded by Kubota and Williams (1967), showing the damage caused by compaction to be less on heavy soil than light soil due to soil cracking in heavy soils. Soils that crack during drying offer an avenue of low resistance for elongation of the growing root through what may be highly compacted conditions. Additionally, even though most of the large pores may be destroyed by compacting forces, clay soils are usually plastic enough to allow roots to penetrate them if there is adequate aeration.

Soil amelioration by earthworm activity has also been documented (Ehlers, 1975; Russell, 1971). Earthworms create channels, carrying organic debris down into the soil and produce granular structure as they pass soils through their system. By voiding soil on the surface they conteract surface crusting and signifantly influence soil porosity (Larson and Allmaras, 1971).

Plant roots can also alleviate compaction (Byrnes et al., 1982) by growth through compacted zones and subsequent decay. Plant roots move particles, create new pores, expand fine pores, leave voids and add organic matter that stabilizes the remaining structural aggregates.

The ability of roots to overcome the mechanical resistance of compacted conditions and, in turn, relieve compaction, to some extent, varies with species. Heinonen (1985; 1986) indicated in his reviews that the taproot of red clover has this ability, as well as other forages of European origin in this study, and to a smaller degree, oil seed rape. The ability of roots to penetrate compact soil increases with diameter (Whiteley and Dexter, 1983). However, narrow cracks in compact soil can be used by thin roots that can grow more rapidly with a limited supply of nutrients early in a plants development (Heinonen, 1985).

This knowledge could he used to improve soil conditions for a following crop. This was demonstrated by Elkins et al. (1977) in Alabama. Roots of Bahia grass possess the ability to penetrate hard layers due to the presence of a fibrous sheath beneath the epidermis of its root. The growth of the Bahia grass roots increased the number of soil pores larger than 1 mm which later enhanced cotton root penetration.

Conservation tillage and no till can utilize natural processes to alleviate compaction. Continuous pore systems, such as left by earthworms or decaying plant roots, which are oriented parallel to compaction forces in the soil profile will help roots cross limited compacted layers (Sommer, 1988; Trousse, 1971). These pores are more predominant in soil where tillage has been signifantly reduced.

Subsoiling

As outlined in earlier sections, compacted soil can restrict root growth as a consequence of too low porosity accompanied by insufficient oxygen supply, excessive mechanical impedance which is affected by soil moisture content, and the destruction of pores of diameters greater than root tips.

Most compaction is shallow enough that it can be alleviated with plowing (Byrnes, et al., 1982; Voorhees et al., 1978). However, a special problem of soil compaction in many arable soils is a severely compacted layer below the plow depth. This severely compacted layer, or plow pan, restricts root growth and available water to the plant roots. Much work has been done on deep plowing, or this layer.

In order to shatter the soil, it must be dry. Subsoiling wet soil will produce a plastic failure when what is needed is a brittle failure. Brittle failure will tend to reduce the average aggregate size while plastic failure tends to increase the average aggregate size (Lipiec, 1989; Byrnes et al., 1982).

By subsoiling, roots may utilize soil nutrients that were unavailable under compacted conditions. However, improvement of root access to soil moisture and increased internal drainage seem to be the main benefits of subsoiling (Unger, 1979).

Discussion of subsoiling was discussed by Cassel (1979), Eck and Unger (1985), Spoor (1982), Swain (1975), Taylor (1986), Unger (1979) and Wind (1982), and others. A good review was conducted by Goldstein (1990).

It has been indicated that when good fertilization and management practices are used in the plow layer, economic response to subsoiling is doubtful (Eck and Unger, 1985). Warkentin (1988) also questioned the undoing of compaction damage by disturbing or ripping. The question results from the fact that ripping may produce large voids between fairly large soil structure units (>2 mm), but compaction may alter smaller units (<1 mm).

The review of subsoiling effects by Russell (1956) indicated that only in 40% of cases were responses positive. Generally speaking, coarse textured soils were less responsive to subsoiling than fine textured soils. It can be related to the shorter duration effect in coarse textured because of the low content of finer soil materials or organic matter to stabilize the pore system (Heinonen, 1985).

In coarse textured soil, where root growth is likely to be impeded by hindered displacement of sand particles due to their surface roughness, subsoiling induced deeper and greater rooting of corn, although the decrease in bulk density was only of the order of 0.1 Mg/m^{-3} (Chaudhary, 1985). Subsoiling which loosened the soil without inverting it promoted deeper root penetration (Eck and Unger, 1985; Swain, 1975; Trouse, 1983; Unger, 1979; Verpraskas and Miner, 1986), but crop yield responses varied with plant species, cultural practices, soil, and environmental conditions during the growth period (Chaudhary, 1985; Eck and Unger, 1985). Soils with higher bulk densities have more potential benefits from subsoiling (Soane et al., 1987).

Subsoiling of loamy soils resulted in deeper root penetration and greater profile water use and increased yield under drought conditions for potatoes (Ross, 1986), corn (Acharya and Bhagat, 1984; Chaudhary et al., 1985) , and winter barley (Ide et al., 1984). The effect of subsoiling was more positive in those soils, where there was a definite layer which impeded root growth and water movement to deeper horizons (Doty et al., 1975; Kamprath et al., 1979; Swain, 1975). This was also shown when Ides et al. (1984), using an oscillating subsoiler in Belgium, found subsoiling increased yields when there was a distinct plow pan under which was a well aerated soil, but not for soils with a compact, poorly drained subsoil.

More positive results were reported by Trouse et al. (1975), Colwick et al. (1981), Mayfield et al. (1978), Webster (1980), Nawrocki (1970), with the effects lasting several years.

One problem with subsoiling is recompaction. When subsequent forces from field traffic are greater than the effective internal strength of the loosened soil, a more pronounced and intensive recompaction of the soil can result plus additional compaction of deeper soil horizons(Gupta and Larson, 1982; Taylor, 1986). The weight of the overlying soil, combined with time can also recompact loosened soil (Soane et al., 1987). Soane et al. (1986) and Larney and Fortune (1986) both used winged subsoilers and found almost complete recompaction following spring seedbed preparation on low organic, fine textured soils. The cycle of 'tillage - traffic - tillage - traffic' must be broken. So, in order for subsoiling to be effective longterm, the source of compaction must be identified and prevented from occurring again.

The expense of subsoiling often makes it uneconomic. Because of the high cost of subsoiling, it has been recommended that it be done only under the crop row (Trouse, 1983). In this way, tires are kept off the subsoiled zone by using mounds to mark the row location and thereby traffic, with its compaction, is limited to areas between the rows. Trouse (1983) reported yield increases of 37 to 200% with corn, 85 to 163% for soybeans, and 163% for cucumbers on soils in the southeastern United States, for this type of in-row subsoiling. The results of in-row subsoiling vary among the studies. Mallet et al. (1985) showed yield increases of 8% to 15% for corn under this system for dry years; for soybeans yield increases of 76% to 81% (Batchelor and Keisling; 1982). Reeves and Touchton (1986) had highly varying results when they compared corn yields on plots using under-the-row and between-the-row subsoiling. Additionally, it is difficult to say that this method would have as dramatic an effect on Ontario soils, where frost action can alleviate compaction to some extent.

Soane et al. (1986; 1987), evaluating subsoiling benefits in Great Britain, also recommended controlled or reduced traffic for extending the life of subsoiling benefits.

Placement of Fertilizer

If compaction restricts a plant's ability to utilize soil nutrients by reducing the soil volume utilized by roots, placing additional fertilizer in a compacted soil may allow the limited root system to draw adequate nutrients because of higher nutrient concentration in a smaller volume of soil.

G. Steinhardt, of Purdue University (U.S.A.) has examined the effect of generous surface application of nitrogen on the yield of corn on compacted soil. Even three years after compaction, applied nitrogen rates of up to 300 lbs/acre have yet to bring corn yields up to those on uncompacted plots. Presently, work is being done on the effect of broadcasting potash. Hallmark and Barber (1981) found that the addition of potassium increased root growth in compacted soil.

Work with pickling cucumbers (Smittle and Williamson, 1977) showed that the effects of soil compaction could be partially offset by increasing the rate of nitrogen fertilization; however, a tripling in nitrogen fertilization did not completely counteract the effect of compaction on cucumber yield.

Some researchers have examined the effect of placement of fertilizer in a band to increase nutrient concentration near the plant roots of plants growing in compacted soil, and as such, increase availability.

Deep fertilization by McEwen and Johnston (1979) demonstrated yield benefits on two of four crops used in the study on a sandy loam soil, after subsoiling. Subsoiling alone increased yields for three of four crops.

Research by Chaudhary and Prihar (1974) found corn yield increased when NPK fertilizer was banded eight inches below the seed, crediting nitrogen and phosphorous with the increased yield. Adding inter-row subsoiling to the treatment increased yields further. A previous study by Vasey and Barber (1963) suggested that banding would have a bigger effect on potassium uptake than phosphorous. Hallmark and Barber (1982) demonstrated that increasing soil potassium helped to overcome many of the detrimental effects of compacted soil.

Not all deep banding work has shown yield increases. Marks and Soane (1987) found yield response to deep placement of phosphate and potash to be greater than a fall plowdown application on only one site of ten. For Hargrove (1985), shallow banding (2 inches) beneath the row had better results than deep banding (24 inches) beneath. or banding at both depths between rows. However, favourable moisture conditions at the soil surface permitted root growth at the level of the shallow placed fertilizer.

In a related principle (adding chemicals to improve growth), hormones have been added to plants growing in compacted soil to improve growth and yield (Alejar, 1980 ; Wilkins, 1976). Wilkins (1976) showed that the addition of 3,5-di-iodo-4-hydroxybenzoic acid (DIHB) would improve the root development of pea seedlings in compacted soils. Root length was increased substantially with small increases in the dry weight of the shoot and root. Alejar (1980) found that the low concentrations of ioxynil or 2,4-D significantly increased the root growth of wheat and barley seedlings.

MEASUREMENT OF SOIL COMPACTION

Root Growth

Commonly used parameters used to measure soil compaction are bulk density and penetrometer pressure (penetration resistance, soil strength). Penetrometer resistance is defined as the ease with which a probe can be pushed into the soil and in a given soil it will depend on the bulk density and soil water content. The penetrometer resistance will increase with higher bulk density and lower soil water content.

Much work has been done to relate penetrometer readings to the actual resistance encountered by a growing root under compacted conditions. A good review and much discussion is found in Glinski and Lipiec (1990).

Penetrometers does not exactly measure the forces encountered by growing roots. Probe angle and diameter, speed of penetration, method of probe advance into the soil, as well as friction on the metal-to-soil surface can affect the correlation between penetrometer readings and normal soil resistance. Gooderham (1977), and Jung La et al. (1985), indicated that standardization of penetration resistance technique would benefit the studies of root growth. Taylor (1974) suggested using probes about equal in diameter to the roots. It was also suggested that the introduction of lubrication and axial and radial expansion systems in future penetrometers would simulate root growth much better (Groenevelt, et al., 1984; Mulqueen, 1977; Russell, 1974; Whiteley, 1981).

Additionally, penetrometers do not measure soil cracking. Soils that crack during drying offer an avenue of low resistance for elongation of the growing root through what may be highly compacted conditions. However, penetrometers do provide useful measures of soil conditions to which root growth can be referred.

Groenevelt (1988) examined the forces encountered by a growing root by employing the use of a probe (or needle) of very small diameter (150 pm). The tip resistance data of the probe can be analyzed to produce the penetrability characteristic of a soil. Assuming that a given root can temporarily exert a maximum tip pressure, that soil can be probed at different bulk densities to find what percentage of that soil is penetrable by that root. An estimate of potential root growth in a given compacted condition might then be achieved.

Soil Compression Characteristics

There is difficulty in precisely measuring the internal forces of soil when it is under compression. Alternative methods are being sought to measure soil consistency, with techniques that provide for precise definition of soil water and effective stress regimes when the soil is under compression stress (McBride and Bober, 1989). Proposed methods are described in McBride (1988), McBride (1989), McBride and Bober (1989), McBride and Watson (1990), McBride (1991, in print), and McBride and Baumgartner (in print). Once a thorough understanding of the compressive nature of soil is acheived, a better understanding of the interactive forces involved in soil compaction will result.

To make the comparison of compaction effects easier between sites and eliminate the influence of soil texture, the use of indicators based on relative density of soil was suggested. One such indicator was suggested by Eriksson et al. (1974) and explained by Hakansson (1988). The "degree of compactness" of an annually tilled soil layer was defined as the dry bulk density of the same soil in a compact reference state. Very large soil samples were used for bulk density determinations in the field, and, in the laboratory, the reference state was obtained using a very large oedemeter with pressure of 200 kPa. This method was tested over a 15-year period in an extensive series of field experiments (Riley, 1988) on soil compaction. An evaluation shows that the method gives the maximum crop yield at the same degree of compactness irrespective of soil type for most soils, the exception being soils high in organic matter.

Bennie and van Antwerpen (1988) proposed compaction classes to evaluate root-impeding characteristics of compacted soil layers. These classes were based on the degree of compaction being a ratio of bulk density minus minimum density and maximum minus minimum density and were as follows: <0.5, low degree of compaction; 0.5 to 0.6, medium degree of compaction; 0.6 to 0.7, high degree of compaction; and >0.7, very high degree of compaction.

Models

Soil compaction is also described by some numerical models, among which those by Bailey et al. (1986), Gupta and Larson (1982), Larson et al. (1986), Raghavan et al. (1977a, 1977b), and Smith (1985) are the latest. Gupta and Allmaras did a review of models (1987), in addition to Schafer et al. (1990).

Smith's model (1985) is based on the prediction of soil specific volume changes arising from the changes in spherical stress caused by wheel loads and the tire/soil contact areas under consideration. The depth of the soil is divided into elemental layers and the spherical stress increase at the center of each layer, below the center of the wheel load, is estimated. The model may be used to compare the compaction caused by various types and arrangements of wheels.

Bailey et al. (1986) proposed a three-parameter (three levels of moisture) multiplicative model of soil compaction. This model is capable of predicting soil density not only at high levels of soil compactness, but also at low (zero) stress levels with less error than the traditional model.

Boone (1986) discussed relationships between soil compaction and crop growth in three aspects. The first being when there is no statistically significant relation between soil compaction and yield. The others being when yield increases due to compaction, and when yield decreases due compaction.

Gupta and Larson (1982) developed a soil compaction model based on the compression relationship and the Boussinesq equation as modified by Soehne (1953) by introducing a concentration factor to describe different kinds and conditions of soils. Larson et al. (1986) summarized various models to predict bulk density of soils. Raghavan et al. (1977a; 1977b) elaborated an equation describing maximum density changes for clay soil after repeated passes of a tractor tire.

Organic Matter Levels

Is widespread soil compaction in the field the sole result of vehicular traffic? This question has been asked by researcher P.H. Groenevelt, University of Guelph, suggesting that some compaction of top soil is due to declining organic matter levels in soil cultivated to row crops. The decline in organic matter has weakened soil aggregate structure and, with the help of tillage, general soil structure has collapsed, resulting in higher bulk densities and reduced porosity.

NEED FOR FURTHER RESEARCH

The intensity of soil compaction still increases and its effects accumulate below the plow layer. Research is needed to look for ways to alleviate this problem.

With increasing heavy machinery traffic on fields, an important question arises as to when soil compaction has a positive or negative effect on root growth and yields. Numerous studies show that moderate compaction increased crop yield, but intensive compaction decreased it. This response could be studied more closely to determine which factors or combination thereof are responsible for these reactions. It also could be further studied for the influence of regional physiographic properties, however field studies in regions with similar climactic conditions to Ontario have been done (Voorhees in Minnesota, U.S. and Hakansson in Sweden, for example).

It seems that soil moisture status, whether it is adequate or excessive often appears to have a great influence on nutrient availability and uptake. Perhaps this suggests the role that irrigation of compacted soils could play in alleviation of compaction induced stress in times of moisture deficits.

Improvements in genetic and management technology are areas of research that would promote the reduction of soil compaction. The genetic development of crop varieties that hold their fruit quality longer could allow harvest traffic to remain off the fields in times of wet soil conditions. Improvement in herbicide performance and seeding methods could reduce the number of trips required.

There are some indications that compaction increases herbicide injury to plants. Further work is needed to measure and understand this interaction.

It is clear that soil compaction affects aeration and gas diffusion and that this effect is more complex than a simple decrease in total pore space. Research is needed on both plant roots and microbes, on the effect on microbe flora, and most importantly, on interactions between the soil physical system, microbial activity, and plants (Pascoe and Myrold, 1988).

The present methods for studying the pore system have not been appropriate for studying the mechanical specifics of soil rootability (Boone, 1986; Boone et al., 1986). The indirect physical methods that are used for measuring the pore size distribution are not appropriate for the largest pores. Direct physical measurement of pore sizes can be accurately measured but more important characteristics, such as the continuity and direction of pores are more difficult to measure (Boone et al., 1986).

The possible role of ethylene in impeded root growth has still to be researched. Whether the reduction in root extension is due to the direct action of elevated levels of IAA or to its stimulation of ethylene production is also undetermined.

Standardization of reporting of soil conditions at the time of compaction are needed, with moisture level and plant development stage, for example, so that comparison between different studies can be made.

The effect of compaction on disease development and severity has received little attention from researchers. One group (Percich et al., 1989.) has started a long term study with peas, and hopefully results of this research can serve as a model for studies of other soil-borne fungal pathogens such as *Fusarium*, *Pythium*, *Phytopthora*, and *Rhizoctonia* species.

Natural Processes

More research is needed to increase the use of natural processes to alleviate compaction. Perhaps selecting plant species which are more resistant to compacted conditions may alleviate stress conditions. Certain plants that loosen the compact layer in the soil profile may be used. Earthworm activity may contribute considerably to alleviating compaction conditions. Another area needing research could be the breeding of new genotypes that are more compaction resistant or with a certain size of root to penetrate the predominantly small pores that are left after compaction. This approach would also require consideration of what is the optimum size root for plant yield and compacted conditions. Selection of plants and breeding, with the proper soil management, could lead to higher plant efficiency of water and nutrient use by the roots.

The concept of optimum root size is dependent on rooting conditions and availability of water and plant nutrients. An extensive root system causes plants to make more efficient use of fertilizers and water and to be less susceptible to chemical and physical stresses during the growing season. Such a system is more important in soils of limited water storage capacity and low or uneven fertility. However, the plant with an extensive root system puts more dry matter production into the root than it does to the shoot, which can result in decreased yield. A smaller root system can be sufficient in soils of higher fertility and adequate moisture (Glinski and Lipiec, 1990).

Compaction destroys pore structure and increases bulk density reducing overall water storage capacity and root extension capacity. It creates conditions that make for a smaller root system. The smaller system will suffice with adequate moisture provided by rainfall or irrigation. Further research can determine whether increased fertilizer application or specialized placement of fertilizer materials or plant hormones can maintain yield levels under compacted conditions. However, any maintenance or improvement of crop yiels with these amendments will have to be balanced with economic and environmental concerns.

The problem of natural soil cycles that alleviate compaction have received relatively little attention so far. Much more can be learned regarding the mechanism of freezing/thawing (Groenevelt, 1990) and wetting/drying cycles and how it affects compacted soil. Additionally, more research can be done to quantify the extent earthworm populations alleviate soil compaction.

Machinery Systems

Compaction increases draft requirements for tillage. Further research is required in order to quantify this value. Currently, Agriculture Canada has implemented a front-wheel-assist four wheel drive tractor with instrumentation to accurately measure data for tillage research on the go (McLaughlin et al., 1989).

With the current recommendation by researchers (Hakansson et al., 1988) to limit axle loads to 10 tonnes or less, it is time for machinery manufacturers to recognize the soil compaction problems caused by large machinery. New designs utilizing lighter machines or more axles could reduce soil loading. In Israel, some work is being done now to replace large machines with many small, lighter robotic machines that effectively reduce soil loading.

The interest in tracked systems is growing. Further research in this area will help define the long term benefits tracked vehicles have for preventing soil compaction and easing soil loading.

Research needs certainly include the development of production systems and machinery for controlled traffic farming. According to Taylor (1990), "Future farm managers will be confronted with as many decisions as a chess player; but... controlled traffic will be the 'board' they're playing on." He calls for demonstration sites and entrepreneurial progress in this area and predicts that the earliest commercial adoption of controlled traffic systems will be for high value crops.

Ameliorative tillage continues to receive attention from machinery manufactures and growers. Because of the loosening of entire fields is expensive and resource intensive, techniques with local loosening or other amelioration techniques should be further developed.

The need for future research on soil compaction was reviewed by Schafer et al. (1990) as part of ASAE 1990 Summer Meeting, which examined soil compaction. It and another paper (Taylor, 1990) provide good reviews of the progression of compaction research. According to the authors (Schafer et al., 1990), future research on soil compaction should include the following objectives:

1. To develop methods of predicting the force systems, from machinery or other sources, which influence compaction.

2. To develop methods for predicting the propagation of compaction forces (stress propagation) in the soil as a function of the soil texture, soil structure, matrix potential, and time, frequency, and intensity of loading.

3. To develop methods for predicting the soil's response to compaction forces (compaction behaviour).

4. To develop standard, or simple material tests that identify and quantify the parameters pertinent to compaction.

5. To develop specifications for the limits of compactness that are required for optimizing the traction and mobility of machines in the field.

6. To develop specifications of the limits of compactness that may be required by the various aspects of the cropping system (the plant, the fluid and gaseous movements, and the biological and chemical activities).

7. To develop management systems that include the management of compaction for all aspects of crop production.

PREVENTION

In the meantime, the most available method to growers for reducing the effects of compaction is in its prevention of compaction. The following practices, from Pumphrey (1980), suggests how soil compaction can be minimized.

1. Work soil when it is as dry as possible; avoid working the soil when moisture content is at or above field capacity.

2. Increase tire size and number of tires; reduce tire pressure. This reduces soil pressure but increases the area compacted.

3. Reduce weight of equipment.

4. Increase speed without increasing tractor-implement weight or slippage.

5. Reduce traffic; combine several operations into one.

6. Confine wheel traffic to the same path or location for all field operations.

SUMMARY

In recent years, increased mechanization and rationalization has increased the risk of soil compaction in Ontario's processing crop industry. Reports from the field are confirming the compaction damage from increased field traffic.

Soil compaction is a reorganization of soil particles resulting from external compression forces on the soil. Compaction increases the bulk density of soil due to a decrease in the number and volume of large pores, which in turn alters aeration, water infiltration, and hydraulic conductivity, and increase soil strength.

Soil compactibility is dependent on soil texture, with well graded soils compacting more tightly than poorly graded soils.

Soil compaction will increase with increases in soil water content, tire contact pressure, and vehicle weight, or axle load. Compaction will decrease with increased vehicle speed, reduced or controlled traffic, and increased number of wheels carrying the vehicle. The use of tracks to replace tires may reduce soil compaction. At great depth, the stress caused by traffic mainly depends on the axle load. Present data show axle loads above 10 tonnes per axle should never be used otherwise soil may he damaged permanently.

Lightly or moderately compacted soil may not cause reduced yields and may improve yields, especially in dry soil conditions. Yield increases in dry years result from improved soil water and nutrient transport.

Severely compacted soil impedes root growth and development. This restricts a plant's ability to utilize soil water and nutrients by reducing the soil volume utilized by roots. In very wet or very dry soil, compaction multiplies the impact of stress on the plant and reduces plant yield. However, if adequate moisture and nutrients are supplied to the reduced root system, the effect of compaction will be negligible.

Soil compaction can affect nutrient availability. It can increase incidence of soil borne plant diseases and reduce the beneficial microbial population.

There has been relatively little research done on the effect of soil compaction on the yield of processing vegetable crops. Compaction can reduce yield by reducing the quality, weight and size of the fruit. It can delay plant development and maturity, reduce plant stand, height and seedling emergence. Subsoil compaction can reduce yields by delaying planting and other field operations.

The reduction in crop yield and quality due to soil compaction is an economic cost to growers and processors. Compaction also increases input costs.

The alleviation of compacted conditions can result from freezing/thawing and wetting/drying cycles but this effect is limited to the upper layers of soil, especially in the short term. Research has shown that the effects of subsoil compaction persist for some time even in areas with heavy frost. The alleviation of subsoil compaction may result from the growth of plant roots or the action of earthworms.

Subsoiling, as examined by research, has shown mixed results, with in-row subsoiling showing the greatest benefits. The placement of fertilizer to compensate for compaction-reduced yield reductions has benefits and is receiving attention.

Further research is needed to better understand the nature of soil under compression, the mechanics of plant growth under compacted soil conditions, and the process of compaction alleviation. To reduce the risk of soil compaction new machinery and crop production systems need to be developed.

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