Agriculture
Canada

Research Branch
Direction générale de la recherche

Technical Bulletin 1

Pedogenetic and Induced Compaction in Agricultural Soils

Research Station,
Fredericton, New Brunswick

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Research Branch
Agriculture Canada
1980

Copies of this technical bulletin may be obtained from

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Également disponible en francais sous le titre
«Compacité pédogénétique et induite des sols agricoles»

TABLE OF CONTENTS

INTRODUCTION

For centuries, farmers have been observing the relationship between plants and their environment to develop the best means of cultivation and to ensure good production to meet human needs. In the past, most people were more concerned with the surface layer of the soil and they attached little importance to the role of subsoil or subsurface layers in crop or forest production. In recent years, however, with increasing pressure on land resources, we have started to pay more attention to what lies beneath the surface layer and to its effect on plant growth.

Subsoil layers are extremely important to crop production, pasture management, forest growth, soil conservation, and the construction of buildings, highways, and airport runways. For agriculture, excessive compaction of subsoil is believed to cause or be related to some reduction in the productivity of many soils because deeper layers have important effects on soil moisture regime and aeration capacity. These subsoil layers may also supply certain plant nutrients. Furthermore, fertility and permeability of the subsoil have a direct influence on erosion hazards when soils are used for crop production (Nowland 1976).

Undesirable compaction levels may be due to naturally occurring or genetically derived edaphic conditions (Winters and Simonson 1951) or due to "induced pans" caused by the manipulation of primary soil particles and aggregates by traction and tillage implements, such as the compression of soil by vehicular traffic (Raney et al. 1955). The mechanics of induced pans and their effect on plant response have been well documented, mainly in USA (Gill and Vanden Berg 1968, Rosenberg 1964, Barnes et al. 1971). A recent series of articles (Voorhees 1977, Robertson and Erickson 1978) describes the problem in more popular language.

This bulletin deals primarily with soil compaction problems, especially in Eastern Canada. However, where necessary and appropriate, more recent and relevant work from elsewhere is included.

CAUSES OF SOIL COMPACTION

The two main types of hard subsoil layers are the naturally occurring or genetically derived dense subsoils and the induced or anthropogenic (caused by man's activity) compact layers.

Naturally occurring or genetically derived dense subsoils

These dense subsoil layers are formed under the natural geologic processes of soil formation either by physical phenomenon as in tills

(Legget 1976, Goldthwait 1971, Milligan 1976) or by chemical cementation of soil particles as in fragipans and ortsteins (Wang et al. 1974 and 1978, Grossman and Carlisle 1969).

Soils developed on till. In the Pleistocene period, over 30% of the land area was covered by ice. At present, about 10% of the world's land area is covered by ice. Consequently, glacial deposits or tills are of particular significance in Canada because in some form they cover most of the land area.

Till is usually a mixture of soil material that ranges from clay size to boulders, but the percentages of any one size may vary greatly from place to place. The variation in the character of till deposits across Canada is discussed by Prest (1961) and Milligan (1976). Thus, the heterogeneous nature of till deposits in situ tend to make the depth and thickness of till horizons variable, from less than a metre to several metres. Till deposited from the base of the ice is commonly referred to as "basal till" and till formed from material accumulated on the surface of the ice and let down from the surface as the ice melted is referred to as "ablational till." Most geologists consider basal till to have been deposited from the base of moving ice by a "plastering on" effect, producing what some refer to as "lodgement till." Others consider basal till to be deposited by melting at the base of stagnant ice. Both methods may be valid and the resulting unstratified, unsorted mixture of material known as till is usually very dense, having a bulk density of 1.8-2.1 g/cm^3 (DeKimpe et al. 1976). Such dense subsoils, just below the plow layer, restrict plant root penetration and downward movement of water and cause serious problems in crop production in Eastern Canada (Soil physical problems and crop production in Eastern Canada 1976). There are millions of hectares of such land across the country. New Brunswick has about 2.5 million hectares.

Fragipan soils. The term fragipan, from the Latin root meaning brittle, was proposed in 1946 even though the kinds of horizons that are designated "fragipans" were recognized early in the century and were commonly called "hard pans." A complete history and description of fragipans is given by Grossman and Carlisle (1969).

Nova Scotia has about half a million hectares of soil with fragipans. Although such soils do occur in other parts of the Atlantic Provinces, Quebec, and Ontario, their extent is not as large as it is in Nova Scotia. Wang et al. (1974), DeKimpe (1970), and DeKimpe and McKeague (1974) have described the properties of fragipans found in Nova Scotia and Quebec. Fragipans have several characteristics, which, though not necessary to the definition, form a part of the general description applicable to most fragipans. They include high silt, very fine sand or fine sand or low clay contents (usually less than 25% clay); low organic matter content, medium to high bulk density when moist (mostly exceeding 1.6 g/cm^3); low or very low saturated hydraulic conductivity (0.02-2.5 cm/hour); well expressed mottling; presence of bleached cracks in fracture planes that form a coarse polygonal pattern on a horizontal plane; weak pedological structured expression within the polyhedrons outlined by the bleached cracks with clearly identifiable and planar upper boundaries; presence of bodies of moved clay and few roots, with those present largely restricted to the cracks between large polyhedrons.

Ortsteins. In 1862, Senft (quoted by Wang et al. 1978) named the hard cemented brown layer of sand occurring below the bleached horizon of heath podzols as ortstein. In recent years, ortsteins generally refer to the strong cementation of podzol and podzolic B horizons with iron and manganese or organic matter.

In Canada, ortsteins were observed in New Brunswick as early as 1940, but they were referred to as hard pans without calling them ortsteins (Stobbe 1940). Likewise, Harlow and Whiteside (1943) in Nova Scotia, Baril and Rochefort (1957) in Quebec, Langmaid et al. (1964) in New Brunswick, and Wells and Heringa (1972) in Newfoundland encountered such hard pans in routine soil surveys of their respective jurisdictions.

Ortsteins appear to have a widespread distribution in the boreal and subarctic zones of Quebec. They also occur near the east coast of New Brunswick and in the Annapolis Valley of Nova Scotia. Minor areas occur in sandy material elsewhere in the Atlantic Provinces. Recently, these hard pans were recognized as ortsteins formed with iron and manganese (Wang et al. 1978). Properties of ortsteins have been studied extensively by Moore (1976) in Quebec and by Brewer et al. (1973) and McKeague et al. (1968) in Newfoundland.

The bulk density of cemented B horizons exceeds that of the noncemented B horizons and varies between 1.2 and 1.8 g/cm^3 (Wang et al. 1978), which is generally lower than the bulk densities of either the fragipan or basal till. Consequently, the cemented ortstein horizons do not seriously restrict water movement except in some periods of very intensive rainfall.

The ortstein soils usually develop in acid sands to loamy lands and occur most commonly under poorly drained conditions. The presence of ortstein soils indicates a poor capability for forestry and agriculture because plants may suffer from droughtiness during the growing season as a result of a shallow rooting zone.

Induced compact layers

Induced compact layers caused by heavy machines and agricultural implements may be found to a certain degree almost all over Canada

(Bolton and Aylesworth 1959, Bolton et al. 1979, Bourget et al. 1961, Feldman and Domier 1970, McKyes et al. 1975, Raghavan and McKyes 1977, Raghavan et al. 1976, 1978, Saini and Hughes 1972, Saini and Lantagne 1974).

The continuous cropping of row crops like potatoes and corn and the ever-increasing size of agricultural machines are perhaps the major causes of induced compaction in Eastern Canada (Saini and Hughes 1972, Raghavan et al. 1979). It has been reported that the average horsepower for new tractors increased each year by 1.8 horsepower from 1956 to 1966 (Purnell et al. 1969). This trend to heavier machines is continuing. It is apparent now that the sandy loam and loam soils of Prince Edward Island that are under continuous potatoes and corn have an induced compacted layer of such extreme density and low permeability that serious erosion occurs on slopes as gentle as 3% (Nowland 1976).

Another cause of compaction and subsequent reduction in crop yield in some agricultural areas of northern Ontario is the installation of pipelines (Culley, private communication 1978). The data seem to indicate that subsequent to pipe installation with the use of heavy earth-moving equipment, the soil bulk density in that vicinity increased by 10% with a resulting average decrease of 40% in crop yields. Saturated hydraulic conductivity was also 30-40% lower than those of soils adjacent to the right-of-way. Compaction can also be caused by intensive stocking of grassland with cattle (Hughes 1974); however, no figures are available in Canada.

It has been generally believed that compaction induced by wheel traffic was not a problem north of the hard-freeze line. Therefore, the most active agent that breaks up compacted layers and ameliorates undesirable conditions was considered to be freezing and thawing of soils (Gill 1971). However, studies in New Brunswick (Saini 1978*a*) and elsewhere (Blake et al. 1976, Voorhees et al. 1978) have discounted this theory; therefore, subsoil compaction may persist in northern colder climates despite deep frost penetration. Several factors that may influence the formation of the induced pan follow.

Effect of particle size distribution. Although the influence of particle size on compaction is emphasized by many workers (Bodman and Constantin 1965), it is quite apparent from our random field observations from the potato-growing areas in New Brunswick that compactibility seems also to be directly related to the number of years a field has been under continuous cropping (Table 1). Soil organic matter per se did not seem to affect bulk density, which shows that heavy equipment may compact the soil irrespective of its high content of organic matter.

Effect of stones. New Brunswick soils have large quantities of stones (Saini and MacLean 1967). In a laboratory study in Maine

Table 1. Influence of soil texture, organic matter (OM), and number of years the field has been in continuous potatoes on the bulk density (D_b) of traffic rows

Site	Sand (%)	Silt (%)	Clay (%)	OM (%)	No. of years under potatoes	D_b* (g/cm^3)
1	36.6	47.4	16.0	4.79	1	1.00
2	27.4	56.6	16.0	6.83	1	1.06
3	34.0	50.0	16.0	6.75	3	1.17
4	24.6	51.4	24.0	6.83	12	1.25
5	25.8	50.0	24.0	5.54	20	1.57

*Mean of 10 replicates

(Struchtemeyer 1960), soils with the varying amounts of coarse material removed were subjected to compaction, and it was found that compactibility of the soil increased when coarser material was removed (Fig. 1).

Effect of soil moisture. Up to the saturation point, any increment in the soil moisture content increases the compactibility of a soil. This phenomenon was observed when a load of 145 kPa (21 psi) was applied to each sample of a Holmesville soil at various moisture levels below the saturation point of 46% (Table 2). These data roughly indicated that, at a pressure of 145 kPa, the average increase was 0.02 g/cm^3 in the bulk density (D_b) of the soil for every 5% increase in soil moisture.

This relationship was also studied in another way. To the samples of Holmesville soil at a D_b of 0.82 g/cm^3 but at various soil moisture levels, the load required to bring the D_b to 1.20 g/cm^3 was recorded with the aid of an unconfined compression apparatus. The results (Fig. 2) suggest that when the compacting force is reduced to half, the soil compacts to almost the same level if it is worked at a soil moisture content of 35% rather than at 25%. These experiments show that even a lightweight tractor compacts the soil significantly if it is used when the soil is beyond a certain moisture content.

Effect of distribution of pressure from tractor tires. The pressure stress-field under the tires of a tractor, trailer, or other implement depends also on the amount of the load, the size of the contact area between the tire and the soil, and the distribution of the surface pressure within this contact area. The pressure distribution in the soil has been determined using semiempirical formulas by Soehne (1958) (Fig. 3).

QUANTITATIVE DESCRIPTION OF SOIL COMPACTION

The compaction process is basically a simple operation--a change in volume for a given mass of soil. This change is variously designated as a change in bulk density, void ratio, fabric, structure, or porosity. However, because of the highly complex character and almost infinite variability of soils, and of the natural and anthropogenic forces acting on soils, the understanding of the soil compaction process has challenged both the best practical farmers and the most capable agricultural scientists.

Most anthropogenic forces are mechanical and fairly easily identified and measured, but most natural forces are difficult to identify and measure. Conceptually, any force can be expressed as

Table 2. Effect of soil moisture content on the bulk density (D_b) of soil when subjected to a load of 145 kPa

Site	Soil moisture (%)	Δ Soil moisture* (%)	D_b (g/cm^3)	Δ D_b+ (g/cm^3)
1	2.4	-	1.09	-
2	10.3	7.9	1.11	0.02
3	15.4	5.1	1.13	0.02
4	20.5	5.1	1.15	0.02
5	25.7	5.2	1.18	0.03
6	30.8	5.1	1.20	0.02
7	35.9	5.1	1.23	0.03
8	41.1	5.2	1.24	0.01

*Change from the initial soil moisture of 2.4%

+Change from the initial D_b of 1.09 g/cm^3

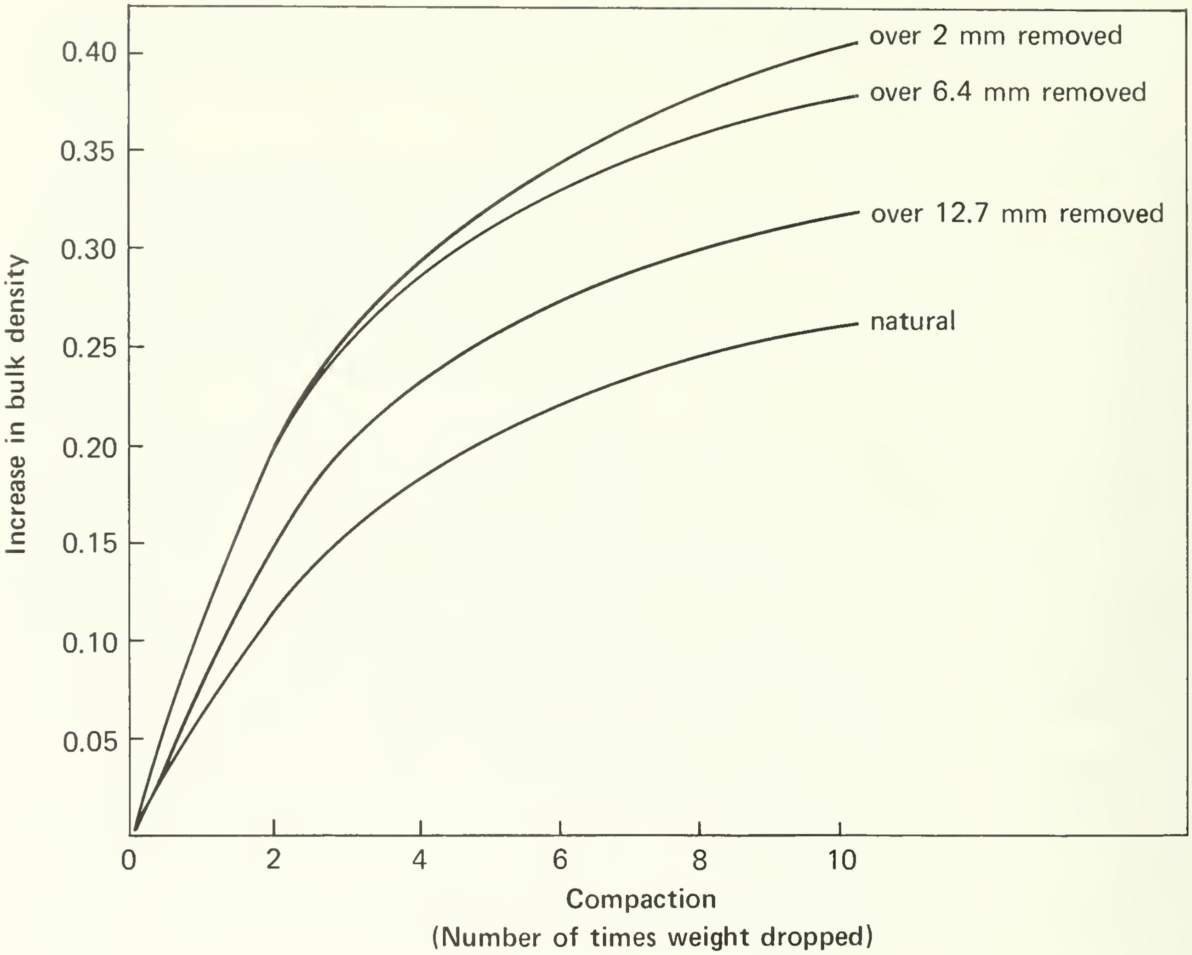


Fig. 1. Effect of stones on soil compactibility (Struchtemeyer 1960).

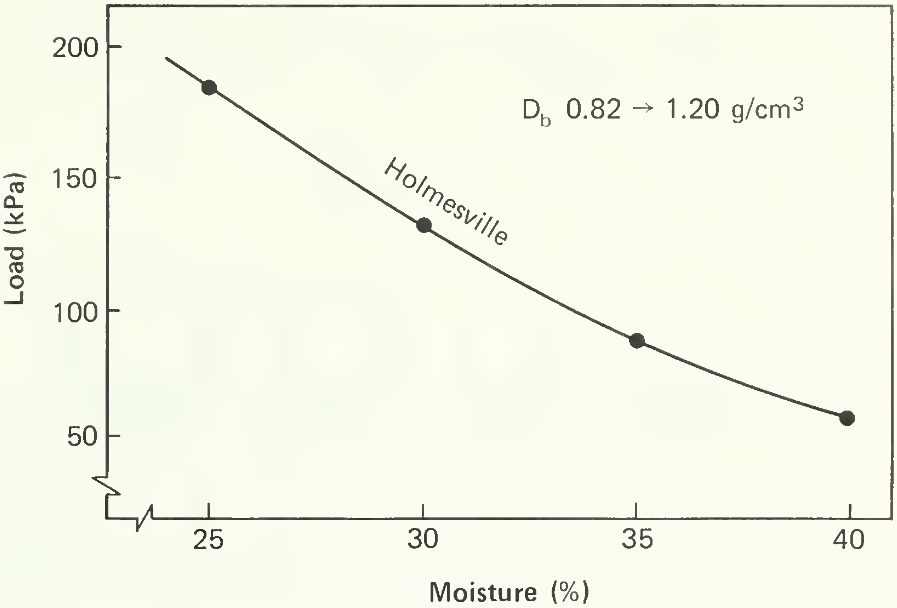
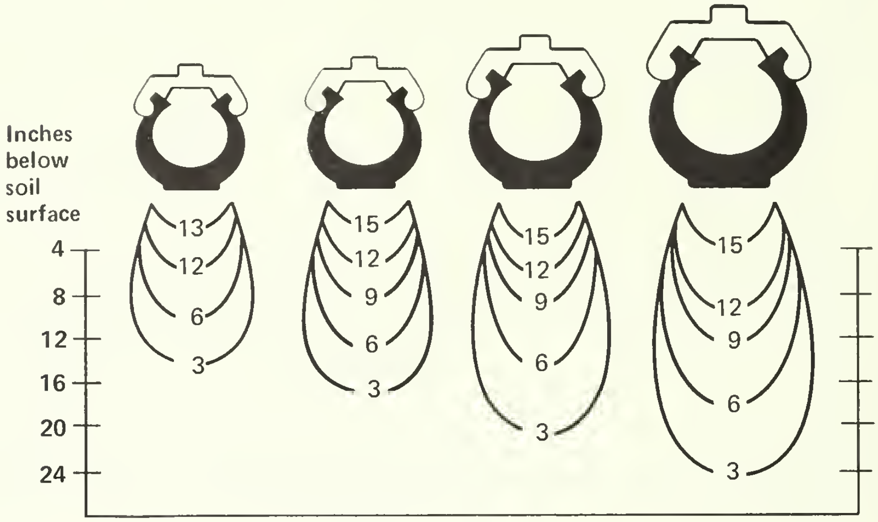


Fig. 2. Effect of moisture on soil compactibility (Saini, unpublished data).

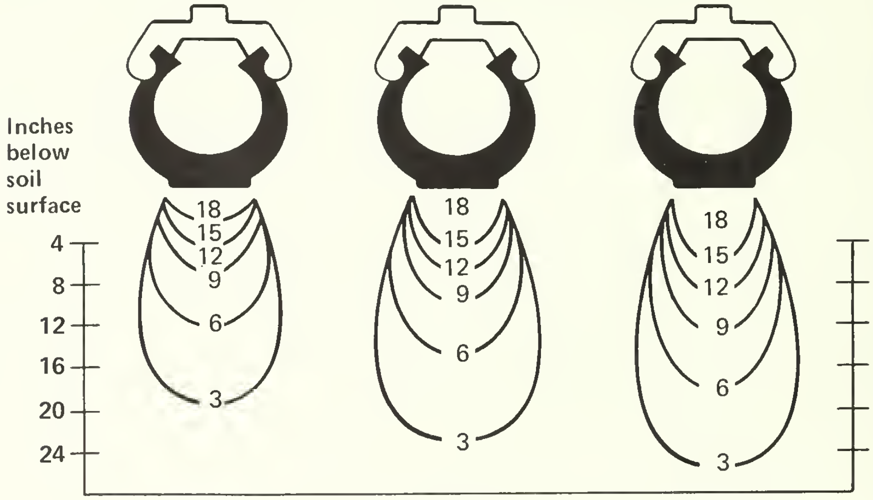
HOW LOADS AFFECT COMPACTION. Diagram shows the difference in soil compaction pressures of different loads in a soil with normal density and water content. Tire sizes are selected proportional to the loads. Maximum compaction pressures will be the same for each. However, a large tractor will transmit pressures deeper and over a wider area.

Tire size	7 X 24	9 X 24	11 X 24	13 X 30
Load	660 lbs	1,100 lbs	1,650 lbs	2,200 lbs
Pressure	12 psi	12 psi	12 psi	12 psi



HOW SOIL MOISTURE AFFECTS COMPACTION. Diagram shows the effect of soil moisture on compaction pressures. All three tires are the same size and loaded equally. The wetter the soils, the deeper the pressures are transmitted.

Tire size: 11 X 28; Load: 1,650 lbs; Pressure 12 psi



Hard dry soil

Soil with normal density & water content

Wet soil

Fig. 3. Effect of load and soil moisture on compactibility (Soehne 1958). (Reproduced from Crops and Soils Magazine, October 1968.)

stress. Therefore, any method that measures a change in the numerical value of a certain parameter or quality, as a consequence of the application of a compacting stress, can be used to measure compaction. Compaction of soil can only be described indirectly. These methods have been described in detail by Freitag (1971) and Black (1965) and only a brief outline is given here.

Methods of measuring soil compaction

Procedures for measuring soil compaction can be grouped into four general classes as follows:

Bulk-density or volume-weight methods. In this group, the bulk-density of the soil is measured with core samplers by immersing irregular samples in a fluid (water, kerosene, mercury, etc.) and using sand, water balloon, or oil in a hole made in the field.

Conductivity measuring methods. In these methods, conductivity of a fluid (such as water and air) and radiation techniques are included. These methods could be further subdivided as follows:

Fluid conductivity

Water conductivity: Shallow-well method, double-tube method, and core method.

Air conductivity: Air permeameter, oxygen diffusion rate.

Pore size distribution: Tension table, mercury intrusion, nitrogen adsorption.

Radiation techniques

Gamma ray: Back-scattering method, attenuation method.

Neutron technique.

Soil strength and stress-strain methods. In these methods, soil strength is measured by penetration tests with penetrometers and shear tests with shear graphs. Stress-strain is measured by pressure cells, strain gauges, and sometimes X rays.

Visual and optical examination. Under certain conditions, changes in soil fabric become apparent to an experienced observer, but to quantify these changes, powerful microscopes must be used to examine the pore size distribution in thin soil sections. Direct measurements using X ray diffraction techniques have also been tried.

General comments on methods

Bulk-density and soil strength are the two methods that have been extensively used by workers to describe soil compaction. Although good correlations between crop yield and soil compaction measured by these methods have often been obtained using one particular soil, there seems to be inherent weakness when these methods are used to compare two different soils or the same soil under various conditions. The results cited by Rosenberg and Willits (1962) were a good example (Table 3) of this, having positive correlation coefficient between bulk density and plant response in Galeston soil, and negative correlation coefficients in Freehold and Penn soils. No explanation of these differences was given, but the authors stated that the interaction of physical properties was probably responsible. Phillips and Kirkham (1962) indicated that the correlation coefficient between penetrometer-bulk density and plant response may decrease with the addition of fertilizer in the same soil (Table 4). Mirreh and Ketcheson (1972, 1973) and Warnaars and Eavis (1972) also suggest that interpreting penetrometer readings in soils of varying moisture contents is difficult.

Thomasson (1978) suggested that, of all the physical measurements, pore size distribution is the most pertinent parameter for plant growth. This also applies to quantification of soil compaction in the field, because for crop production, pore size distribution and compaction are the same. Oxygen diffusion rate (ODR), a measure of pore size distribution that is more sensitive than air capacity measurement, has given good correlation with crop response in the field (Saini 1976). An index for pore size distribution calculated after obtaining the moisture characteristic curve of a soil has been proposed by Cary and Hayden (1973). These measurements are taken in the laboratory from so-called "undisturbed" soil cores. It is quite hard to get a good core sample from brittle or stony soils.

No one method can be used in all situations; the choice of method depends on the particular situation.

SIGNIFICANCE OF COMPACTION IN CROP PRODUCTION

Compaction becomes a problem when it produces changes in soil properties that are of economic significance in crop production. The effects of compaction can be divided into those in which a direct response in root growth or activity can be detected and those that exert an indirect action such as changes in temperature, aeration, and the moisture balance of the profile.

Table 3. r Values for linear correlation of soil physical measurements with growth parameters of barley grown on three soils (Rosenberg and Willits 1962)

Soil	Plant response	Bulk density	Oxygen diffusion rate at 60 mb suction	Hydraulic conductivity	Available water
Galeston	Forage	+0.26	-	-0.16	+0.21
	Grain	+0.55*	-	-0.49*	+0.51*
Freehold	Forage	-0.69†	-	+0.58†	-0.42
	Grain	-0.60†	-	+0.25	-0.13
Penn	Forage	-0.54†	+0.54†	+0.55†	-0.36
	Grain	-0.26	+0.19	+0.41*	-0.47*

*r Value significant at 5% probability

†r Value significant at 1% probability

Table 4. Simple correlation coefficients of yield and average bulk density of different layers for the compaction experiment on Colo clay in 1957 and 1958 (Phillips and Kirkham 1962)

Year	Depth (cm)	Correlation coefficient (r)	
		Existing fertilizer	Added fertilizer
1957	0-7.6	-0.787	-0.567
	7.6-15.2	-0.796	-0.427
	15.2-22.8	-0.527	-0.371
	22.8-30.4	-0.289	-0.063
	0-15.2	-0.812	-0.537
	0-22.8	-0.794	-0.550
	0-30.4	-0.803	-0.526
1958	0-7.6	-0.650	-0.443
	7.6-15.2	-0.720	-0.558
	15.2-22.8	-0.393	-0.665
	22.8-30.4	-0.282	-0.341
	0-15.2	-0.721	-0.658
	0-22.8	-0.693	-0.807
	0-30.4	-0.725	-0.796

Compaction and mechanical impedance

Roots and shoots grow mainly through existing voids in openly structured soils. Whenever they encounter hard horizons they need to exert enough force to deform such horizons. The soil resists deformation and the root elongation is stressed mechanically by the reaction of the soil. Plant growth and consequently yields are affected (see Figs. 4-6).

Although mechanical impedance as measured with penetrometers of various designs has been found to be a useful indication of root penetration, it is recognized that many aspects of root growth behavior do not conform with the action of a blunt penetrometer. Also, the interaction between soil strength and moisture status of the soil may influence penetrometer readings (Mirreh and Ketcheson 1972, 1973). This relationship was documented by Barley and Greacen (1967).

Effect of compaction on soil moisture status

The influence of changes in soil structure and porosity properties on plant growth are less apparent under low moisture conditions than during periods when precipitation exceeds evapotranspiration. The presence of a permanent compacted layer is, therefore, likely to act as a severe restriction to the drainage of excess water. The effect of this condition is usually shown in spring by a reduction in drying rate and a delay in planting as well as the development of poor conditions of aeration after heavy rain during the growing season.

Effect of compaction on nutrient supply to plants

The physical condition of the soil directly affects crop nutrition by controlling the rate and level at which ions can move to the root surface. Indirect effects of soil compaction are through the influence on root extension, aeration, and moisture. When plant nutrients are trapped in the soil where the roots cannot get to them, even the promising new varieties cannot produce what is expected of them (Trouse 1978).

Fertility potential of compacted soil is a complex problem. Of all the major nutrient elements, nitrogen perhaps is the most severely affected because, due to anaerobic conditions, soil microbes are not able to transform ammonium ions into nitrate ions and nitrogen is thus lost to the atmosphere through the process of denitrification. The addition of nitrogen in ammonium form at 112 kg/ha to the same soil type at two bulk densities produced nitrification at a lower progressive rate in the compacted sample (Fig. 7). Therefore more nitrogenous fertilizer is required in a compacted soil than in a noncompacted soil to obtain similar yields. Similar results were found by Bakerman and deWit (1970) (Table 5) where addition of N at 100 kg/ha to a noncompact soil produced potatoes at 35.1 tonnes/ha, whereas only 27.7 tonnes/ha were

Fig. 4. Bent roots caused by mechanical impedance in dense subsoil.

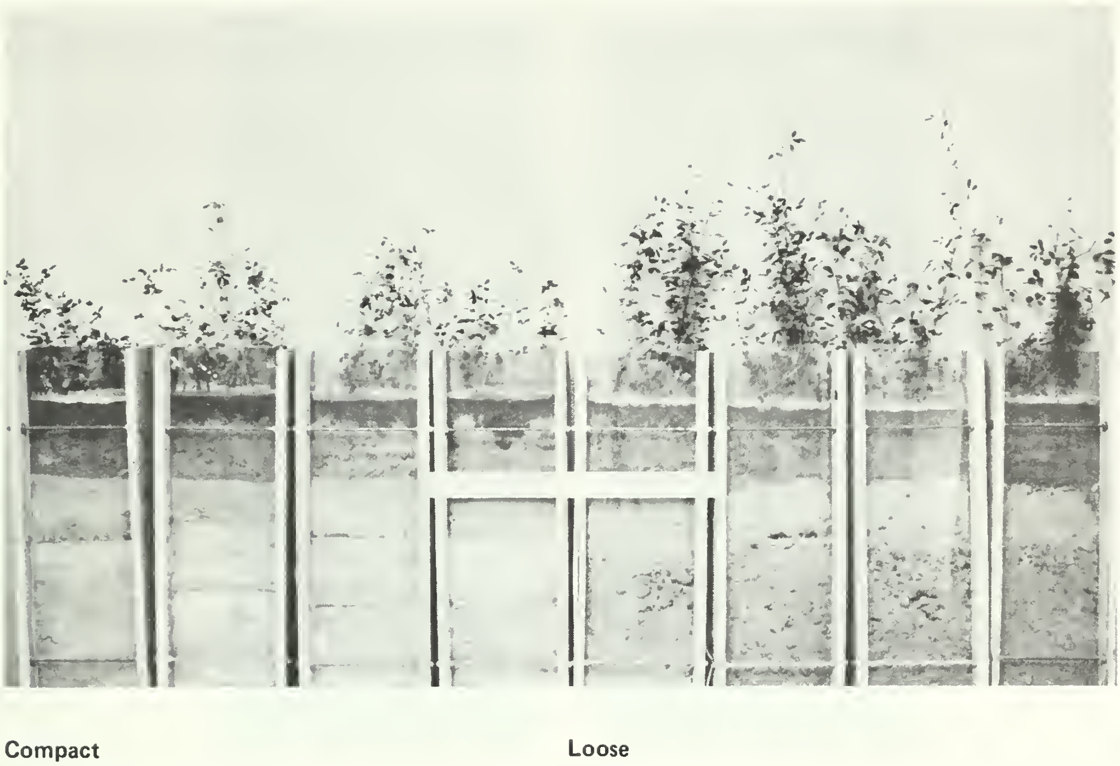


Fig. 5. Improved growth of alfalfa plants in loosened subsoil.

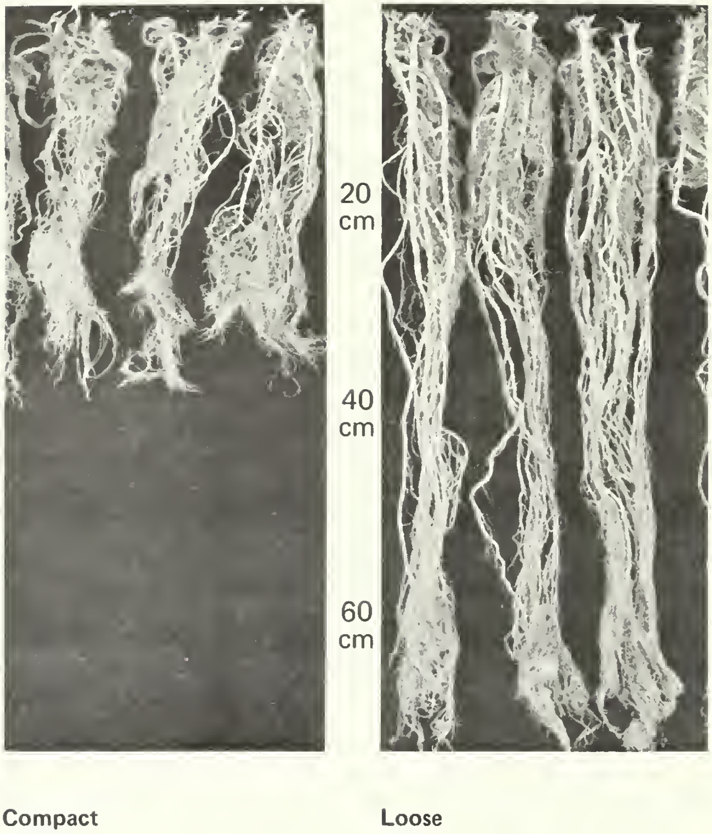


Fig. 6. Depth of alfalfa roots in loosened and compact dense subsoil.

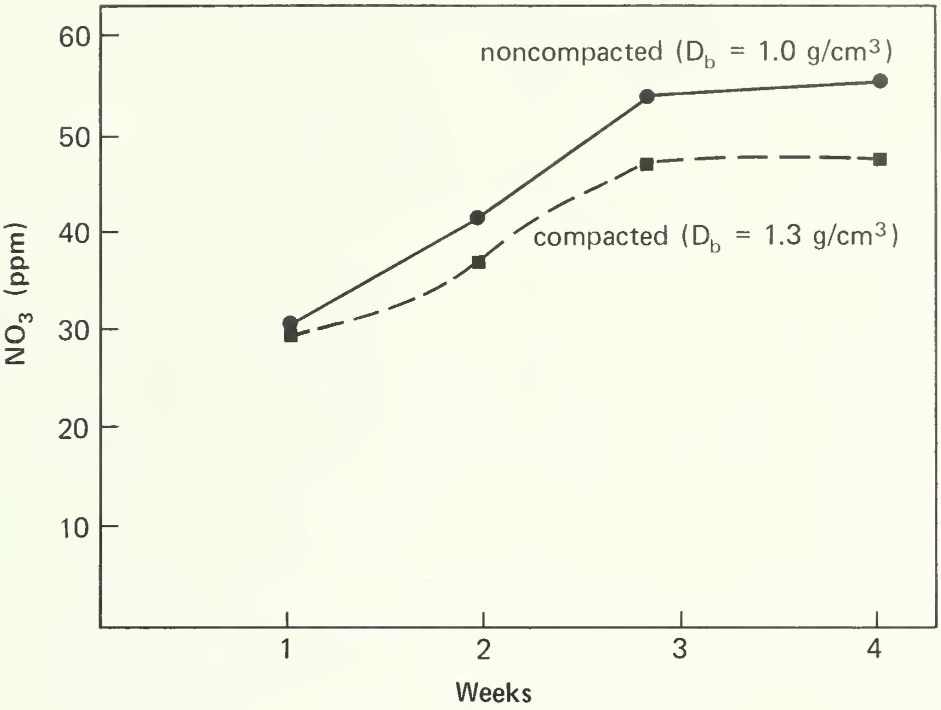


Fig. 7. Effect of compaction on nitrification.

Table 5. Effect of nitrogen on yield of potato in a naturally compact soil (Bakerman and deWit 1970)

N added (kg/ha)	Potato yield (tonnes/ha)	
	Cultivated soil	Compact soil
100	35.1	27.7
200	36.7	37.5
300	38.2	38.1

obtained with a comparable application of nitrogen fertilizer on a compact soil. These results show that twice as much fertilizer is needed for compact soils as for noncompact soils to obtain the same yield. A recent study in Ontario by Bolton et al. (1979) also showed that corn yield on Brookston clay soil can be maintained at a fairly high level on a monoculture basis by using adequate fertilizer, but yield is achieved in part at the cost of soil impairment and inefficient use of fertilizer.

Effect of compaction on yield of farm crops

Due to the many factors that influence crop yield, it is rarely possible to establish any direct relationship between changes brought about by specific compaction treatment and yield. However, there is considerable evidence showing that yield decline in the field can occur following compaction even with a slight change in this soil physical property. Table 6 shows that, when soil bulk density changed from 1.08 g/cm^3 to 1.17 g/cm^3, the yield of potato tubers in New Brunswick declined by 13%. Similarly, when total pore space decreased from 52.2% to 49.3%, yield of sugar beet in Ontario declined by more than 11% (Bolton and Aylesworth 1968). Bolton et al. (1979) in a 13-year program showed that continuous corn culture was associated with soil compaction. For compacted soils, crop yields were at least 12% lower in the monoculture than in rotations. Studies by Raghavan et al. (1979) in Quebec showed that plots with moderate compaction produced a total average plant dry matter yield of 12 500 kg/ha, whereas heavily compacted plots produced 9000 to 9700 kg/ha.

MANAGEMENT OF SOILS HAVING COMPACTION PROBLEMS

A number of compaction-related factors, as stated in the preceding section, that affect crop yield apply to both naturally occurring compacted soils and soils with induced compaction. However, the management of the two types of compaction varies because of the different problems created by the depth and thickness of the hard layer.

Naturally occurring or genetically derived dense subsoils

Deep tillage, which means disturbing, shattering, chiseling, or subsoiling up to 90 cm or deeper, has been tried by various workers for improving crop production in naturally compacted soil. The results obtained from such studies have been sometimes contradictory and often confusing. Some success in improving crop production in fragipan soils with the aid of deep tillage has been reported in Nova Scotia (Hilchey, private communication 1978) but a 3-year field study in New Brunswick has shown that subsoiling alone is not very effective in increasing corn

Table 6. Effect of traffic on soil physical properties and potato yields (Saini and Hughes 1972)

Tractor passes	D_b (g/cm^3)	O_2 diffusion rate ($mg/cm^2 min^{-1}$)	Soil water potential (kPa)		Marketable tuber yield (tonnes/ha)
			10 cm deep	15 cm deep	
0	0.99	67.96	2040	1970	28.1
3	1.06	67.58			24.3
6	1.08	67.58			23.9
12	1.17	58.94	1040	2280	22.1

or alfalfa yields in soils developed on compact basal till (Saini 1978*b*). However, crop production was increased when subsoiling was used in combination with tile drainage. Incorporation of amendments such as lime, manure, and sawdust increases crop yields in fragipan and basal till soils in the first year of the operation (Bradford and Blanchar 1977, Fiskell and Calvert 1975, Saini 1978*b*). A 5-year study by Robertson and Volk (1968) showed that yields of maize, Bahia grass, and sorghum were not improved by either deep mixing or deep amendment incorporation compared to normal practice. Thus, to obtain higher yields, periodic deep-tillage operations may have to be undertaken, which is expensive because of the high cost of fossil fuel.

The use of small quantities of plant growth regulators in the topsoil has been proposed as a solution (Saini 1979). A greenhouse study has shown that a small quantity of 3,5-diiodo-4-hydroxybenzoic acid (DIHB) mixed with the topsoil gives favorable results for root elongation (Fig. 8) and shoot yields.

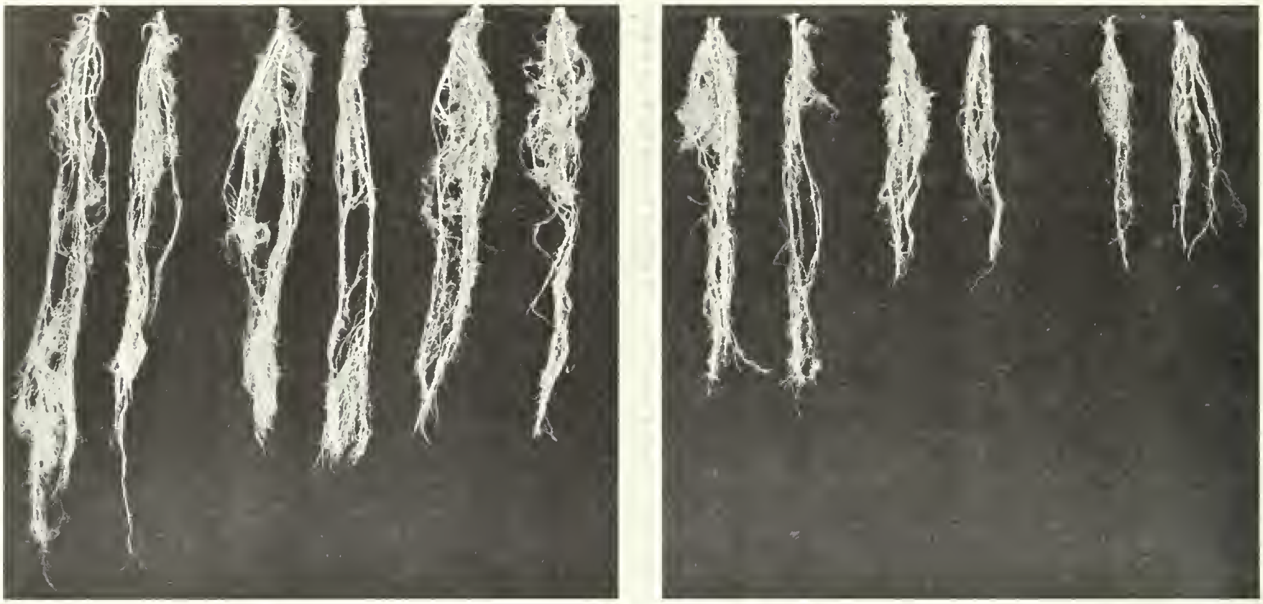
Induced compaction

Since the publication of Modern farming and the soil by the Agricultural Advisory Council (U.K.) in 1970, soil structure and soil compaction have become of increasing concern. Therefore, any practices that minimize the problem can be beneficial over a long period. For example: Do not work the soil when it is too wet; avoid plowing to the same depth each year, especially if the tractor tires run in the furrow; remove tractor weights when they are not needed for traction; and work the ground only as many times as necessary to establish a good stand.

No one tillage method, however, is best for all situations (Bolton et al. 1977). These workers found that plowing at 10 or 20 cm deep was more effective for increasing the yield of corn than plowing at 30 cm deep, but the results with tomatoes were the reverse.

A study commissioned by the National Research Council of Canada (1971) suggests that aerial spraying of potatoes is preferable to ground methods, which compact the soil. Incorporating crop residues or some other organic material, such as tree bark, may improve the physical condition of the soil (Saini and Hughes 1975) and minimize the effects of heavy equipment used in potato production. Most of the induced hard pans are caused by continuous cropping of row crops such as corn and potatoes. Thus, it is usually advantageous to use a crop rotation that includes a deep-rooted legume (Bolton et al. 1976, 1979).

Eliminating existing compaction is a separate problem. Ordinary conventional subsoilers, which reach 30 cm deep, can be effective in penetrating and breaking the plow pans, because such pans occur only at about 20 cm deep. Subsoiling is being used as a satisfactory practice by many farmers in Eastern Canada. To maximize the benefits of



Loose + Lime

Loose

DIHB

GA_3

Control +Lime

Control

Fig. 8. Comparison of root elongation with subsoiling plus lime, gibberellic acid (GA), and 3,5-diiodo-4-hydroxybenzoic acid (DIHB) addition to topsoil.

subsoiling, it should be done when the soil is dry and the hard layers are more likely to shatter. Under moist conditions, the slot formed by penetrating the hard pan may disappear quickly.

Research has also looked at perforating compacted soil layers with certain deep-rooting plants. Elkins et al. (1973, 1977) reported that the Pensacola strain of Bahia grass penetrated compacted soil layers, and when the root system decayed, the root channels remained open for penetration by cotton roots. When after 4 years in Bahia grass, a field was planted to cotton, the cotton produced a deeper root system and the yields were more than doubled. Bahia grass, however, is best adapted to the mild climate of the southern coastal area, but Elkins et al. (1977) suggest that tall fescue may be a good candidate for colder climates.

CONCLUSIONS AND RECOMMENDATIONS

Soil compaction, whether natural or induced, is a complex problem. The state of compaction of a soil largely determines the physical and related chemical conditions that control the response of plants in a permanent agriculture. Therefore, an understanding of the processes of modifying and controlling the compaction of soils and a knowledge of the means of measuring compaction are essential for effective crop production. However, soil compaction is measured indirectly after the application of a compacting stress such as bulk density, penetrometer reading, hydraulic conductivity, or oxygen diffusion. No one method can be used in all situations; therefore you must choose the method that will yield the best results for your particular situation.

Any practice that reduces induced compaction caused by the continued use of heavy equipment can be beneficial. Consider the following recommendations:

- Do not work the soil when it is too wet.
- Avoid plowing to the same depth each year, especially if the tractor tires run in the furrow.
- Remove tractor weights when they are not needed for traction.
- Work the ground only as many times as is necessary to establish a good stand.
- Incorporate crop residues or some other organic material, such as manure, when possible.
- Avoid continuous cropping of row crops such as corn and potatoes.
- Use a crop rotation that includes a deep-rooted legume.
- Use a conventional subsoiler, which reaches 30 cm deep, to penetrate and break the plow pans.

The management of naturally occurring compact soils is a problem. Although crop yields can be improved by deep tillage (deeper than 90 cm), the effect is only short-lived. Deep tillage, along with tile drainage, is effective but also very expensive. The physical properties of the subsoil can be improved and crop yields increased by incorporating amendments such as manure, lime, and sawdust. Unfortunately, however, at present there is no equipment that can be used to achieve this economically. The use of some chemicals shows promise, but their cost is too high for commercial crop production.

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