Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2018, 5(9): 701-709

Review Article ISSN: 2394 - 658X

Overview of Engineering Problems of Soil Compaction and Their Effects on Growth and Yields of Crops

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ABSTRACT

Soil compaction constitutes serious engineering problems in agriculture that researchers have been contending with to proffer sustainable solution. This review work was carried out to contribute to the fixing of the problems. Effects of soil compaction have eaten deep and are adversely affecting the production of food and fibre throughout the world. Soil compaction occurs when soil particles are pressed together, leading to increased density and reduction in soil pore space. Thus, physical structure of the soil finds it difficult to support and applied mechanical stress leading to loss of soil structural units, decrease in soil volume, increase in bulk density, decrease in porosity and reduction in hydraulic conductivity of the soil. Compacted soils have reduced available water capacity. The change in pore space restricts root growth, and the gas exchange necessary for plant growth. Compaction restricts infiltration of water, increasing runoff and erosion, leading to the loss of valuable nutrients. Soil strength, cone index, bulk density, porosity, moisture content, erosion and runoff, poor plant growth and yields are the major parameters used as indicators of soil compaction. The problems of soil compaction are a global concern. As farmers continue to till the soil for the purpose of food and fibre production to meet the need of growing world population; prevention and alleviation practices should be taken into consideration to avoid the negative effects of soil compaction. Farmers are advised to carry out precision traffic agricultural practice; planting of crops on soils with cone index more than 1.5 kPa should be avoided; deep tillage practices, normally called subsoiling should be carried out on soils confirmed to be compacted. Farmers are advised to cultivate cover crops; incorporation of organic matter into the soil; and practicing of mixed farming in order to alleviate soil compaction menace.

Key words: Soil Compaction, Penetration Resistance, Crops, Growths, Yield

INTRODUCTION

Soil compaction is a well-established corpus of investigation generating over 3,000 references in the last quarter century. Many aspects of the effects of soil compaction have been studied [1]. Soil compaction occurs when soil particles are pressed together, leading to a reduction in the soil pore space. [2] Reported that it is a process that brings about an increase in soil density or unit weight, accompanied by a decrease in air volume. Thus soil compaction results when the physical structure of the soil finds it difficult to support an applied weight or mechanical stress leading to a coarsening or loss of soil structural units, decrease in soil volume, increase in bulk density, decrease in porosity and reduction in hydraulic conductivity of the soil. Compacted soils have reduced available water capacity. The change in pore space restricts root growth, and the gas exchange necessary for plant growth and yield. Compaction restricts infiltration of water, increasing runoff and erosion, leading to the loss of valuable nutrients. [3-8]. According to [9] and [10], soil compaction refers to the formation of well packed soil, often at the bottom of the cultivated layer.

[11] Explained that soil compaction is the main form of land degradation, affecting more than 11% land area. [12] Added that soil compaction is a worldwide problem in modern agriculture associated with overuse of heavy machineries and intensification of cropping systems.

[2] and [13] revealed that compaction of agricultural soils is a global concern since it has adverse effects on the environment and consequently, agricultural production. According to them, it is estimated to be responsible for the degradation of an area of 33 million ha in Europe and is one of the major problems facing modern agriculture in the world today. According to [1, 14-16], soil compaction reduces crop growth and yields, by restricting root development

as well as water and air movement in the soil. Soil compaction in the surface layer can increase runoff and soil erosion, thus increasing soil and water losses.

According to [17-18] heavier and more powerful tractors and machines have been used on farms throughout the world. The aim is to reduce the human drudgery and labour; and corresponding increase in farm size and individual operator productivity. This has resulted in increased load on the soil causing compaction. In other words compaction is caused by working or driving on wet fields (wheel traffic), animal traffic or poor grazing management or natural process or raindrop impact [19-21]. Wheel traffic and vibration caused by large equipment results in soil compaction. Moreover, soils with high clay content are naturally susceptible to compaction due to their small particle constituents [22]. [23] asserted that many human activities such as land clearing and development, and tillage normally carried out before planting, weeding and harvesting operations have been identified as major causes of soil compaction.

Parameters such cone index, bulk density, porosity, runoff, erosion and stunted plant root development are indicators of soil compaction. Soil compaction leads to increase in penetration resistance to crop roots, increased bulk density and reduction in pore spaces – air and water contents of the soil. It is normally measured by cone penetrometer in terms of penetration resistance or cone index. In general an increase in compaction, as indicated in increased resistance to penetration, indicates reduced air and water movement within the soil, less favourable conditions for plant growth, and increased erosion potentials [17, 24-26].

[27] asserted that compaction is regarded as the most serious environmental problem caused by conventional agriculture; it is the most difficult type of degradation to locate and rationalize, principally as it may show no evident marks on the soil surface. Unlike erosion and salting that give strong surface evidence of the presence of land degradation, degradation of soil structure requires physical monitoring and examination before it is uncovered and its extent, nature and cause resolved.

Considerable time, money and energy are required to alleviate soil compaction. Such effort can be well justified in situations where, because of dense soil conditions, soil aeration, root development and water percolation are severely impeded [2, 17, 19, 20, 28-33].

The objectives of this study are - review the engineering problems of soil compaction and their effects on growth and yields of crops, with possible measures for minimizing and alleviating them.

CAUSES, IDENTIFICATION, AND MEASUREMENT OF SOIL COMPACTION

Causes of Soil Compaction

There are several forces, natural and man-induced, that compact a soil. These can be great, such as from a tractor, combine or tillage implement, or it can come from something as small as a raindrop. Listed below are types of soil compaction and their causes.

Raindrop Impact

This is certainly a natural cause of compaction, and we see it as a soil crust (usually less than 1/2 inch thick at the soil surface) that may prevent seedling emergence. Rotary hoeing can often alleviate this problem. Drops of rain cause splash erosion, which disturbs the top layer of soil particles and causes formation of a thin surface crust that blocks water from reaching plant roots.

Tillage Operations

Tilling the soil accelerates breakdown of organic materials that inhibit compaction. It can also damage soil structure, the arrangement of mineral particles in relation to pore space, especially if soil is tilled when it is wet. Over the years, repeated tillage orients all of the soil particles in the same direction, causing a layer of compacted soil (a plow pan) to form directly beneath the area being tilled. Plow pans are mainly a problem on farm fields where the soil is consistently tilled at the same depth.

Continuous mouldboard plowing or disking at the same depth will cause serious tillage pans (compacted layers) just below the depth of tillage in some soils. This tillage pan is generally relatively thin (1-2 inches thick), may not have a significant effect on crop production, and can be alleviated by varying depth of tillage over time or by special tillage operations.

Wheel Traffic

This is without doubt the major cause of soil compaction. With increasing farm size, the window of time in which to get these operations done in a timely manner is often limited. The weight of tractors has increased from less than 3 tons in the 1940's to approximately 20 tons today for the big four-wheel-drive units. This is of special concern because spring planting is often done before the soil is dry enough to support the heavy planting equipment [34]. Heavy farm machinery can create persistent subsoil compaction [35]. An axle load of 10 Mg can cause compaction to penetrate to a depth of 50 cm, and with still higher loads, compaction can reach 1 m deep. Loads as high as 30 Mg per axle are used in many countries. Consequently, soil compaction resulting from farm machinery has become a major concern in agriculture worldwide [36]. Soil is also compacted during building construction, from repeated use of riding lawn mowers, or from off-road parking of automobiles and recreational vehicles. Pedestrian pathways across garden beds and turf areas are also significant contributors to compaction.

Intensity of trafficking (number of passes) plays an important role in soil compaction because deformations can increase with the number of passes [37-40]. Experimental findings have shown that all soil parameters become less favourable after the passage of a tractor and that a number of passes on the same tramlines of a light tractor, can do as much or even greater damage than a heavier tractor with few passes. The critical number of passes was ten (10), beyond which advantages from the use of a light tractor were lost [41] in [18].

Minimal Crop Rotation

The trend towards a limited crop rotation has had two effects: (1) Limiting different rooting systems and their beneficial effects on breaking subsoil compaction, and (2) Increased potential for compaction early in the cropping season, due to more tillage activity and field traffic.

Natural Processes

Soils with high clay content—typical of wetlands and river bottoms—can become compacted due to natural processes. Because individual clay particles are so small, they are more susceptible to being pressed together tightly.

Pasture Grazing

There is a tendency for the soil to become compacted after continuous grazing of animals on the field. [20] reported that regardless of the type of grazing system soil bulk density is increased at field moist condition, and that this effect was most pronounced at soil depths less than 10 cm. He further revealed that there was an increase in penetration resistance and a general reduction in soil water up to a depth of 15 cm. [21] stated that poor grazing management is one of the major causes of soil compaction in agricultural land. According to him livestock traffic develops soil compaction due to repeated pressure in the area due to poor grazing management. Although livestock can break the upper layer of the soil due to hoof action, deep compaction layers develop overtime if left untreated. Soils that are higher in clay content are more susceptible to hoof compaction than sandier soils. He further reiterated that aeration can decrease soil compaction and allow for greater plant root development.

IDENTIFICATION, INDICATORS AND ENGINEERING PROBLEMS OF SOIL COMPACTION

Measurements of fluid flow through a soil provide a meaningful description of compaction, because the fluid conductivity is related, generally, to the amount of pore space in the soil. Air permeability is a measure of air flow through a soil. According to [42] the ideal condition for maximum air permeability is a perfectly dry soil. However, this state is not achieved in practice, and there is no analytical way of correcting for soil moisture. Air-filled porosity is a measure of soil air content. Total porosity is a measure of the pore volume, which can be occupied by air or liquid (water) in the soil. Both may be used to measure compaction, but total porosity is more useful because it is independent of soil moisture content.

One of the most frequently used measures of soil compaction is bulk density. Normally soil dry density is calculated to eliminate moisture content as a variable. Within a given soil, the bulk density provides a measure of how close the soil particles are packed, but does not yield any information about their geometric arrangement or the pore-size distribution [42]. The shrink-swell properties of the Hoytville soil make bulk density a less qualitative measurement, or at least, less useful.

Soil strength, Cone Index, Bulk density, Porosity, moisture content, erosion and runoff, poor plant growth and yields are the major parameters used in measuring soil compaction. Many researchers have used the cone penetrometer because it provides a rapid, simple and economical means of indicating compaction [43].

Bulk density is one of the major indicators of soil compaction. [44] Revealed that due to the lack of research literature, the maximum value of bulk density which may be considered usable by plant is 2.1 Mg m^{-3} in any type of soil. [44] specified that the ideal bulk density for sand and loamy sand is < 1.60 g/cm^3, while > 1.80 g/cm^3 restricts root growth. While for sandy clay and clay loam soils, the ideal bulk density is < 1.40 g/cm^3, and root restricted bulk density is > 1.75 g/cm3. Whereas for silty clay loam, the ideal bulk density is < 1.40 g/cm^3, while 1.65 g/cm^3 restricts root growth. While for clay soils the ideal bulk density is <1.10 g/cm^3, and root restricting bulk density is >1.47 g/cm^3.

On the other hand, in Sandy clay and silty clay soils, the ideal bulk density for root growth is < 1.10 g/cm^3, while > 1.58 g/cm^3 restricts root growth. According to [45] a medium textured soil, having a bulk density of 1.2 g/cm^3 is generally favourable for root growth. However, roots growing through a medium textured soil with a bulk density near 1.2 g/cm^3 will probably not have a high degree of branching or secondary root formation. In this case, a moderate amount of compaction can increase root branching and secondary root formation, allowing roots to thoroughly explore the soil for nutrients [46]. This is especially important for plant uptake or non-mobile nutrients such as phosphorus [47].

MEASUREMENT OF SOIL COMPACTION

Cone penetrometer

Cone penetrometer has been used in agriculture and horticulture primarily because they attempt to measure the actual pressure a root meets when growing into a soil. They are frequently used because they are reasonably easy to operate, give an instant result, and are relatively economical. The applied force required to press the penetrometer into a soil is an

index of the shear resistance of the soil and is called the "cone index" (CI). Thus, CI gives the specifications of the actual probe and the force required to press the probe into the soil. CI can be described:

$$CI = \frac{F}{\pi d2/4}$$

Where F = total pressure needed to force the penetrometer into the soil (Newtons, N), the denominator is the base area of the cone, and d is the diameter of the cone. CI is measured in Pascals (Pa) or N/m^2. CI is dependent on soil and probe characteristics, including cone-base diameter, cone angle, and the surface roughness of the cone, as well as penetration rate and the immediate condition of the soil - primarily moisture content and texture [43, 48-50].

The penetrometer is a stiff metal probe following a straight line through the soil, but because no other method is available as a direct measurement of root growth penetration, it is the best available tool for estimating root growth impedance [51]. One should interpret penetration resistance information very carefully because many factors can significantly affect it, including soil type, soil strength, soil water content, penetration rate, cone size and shape, and surface roughness of the cone.

Surface Nuclear Gauges (SNGs)

Over the past 25 years, the use of SNGs has become increasingly common on construction sites. The SNG was developed for quality control of subgrade and base material compaction during road construction. Because the instrument is currently in use on construction sites, SNGs have also been used as an alternative to traditional excavation methods for determining bulk densities. SNGs are used frequently on construction sites by road and building technicians. When using a surface nuclear gauge, two independent measurements are determined: 1) the wet density of the soil, and 2) the soil moisture content. Wet density is measured by the suppression of gamma waves from a probe lowered from the gauge into the soil. Moisture content is measured immediately below the gauge, as the amount of reflected neutrons hitting the hydrogen in the water. By subtracting moisture content from wet density, dry bulk density is obtained. Both measurements may be derived within a minute [49].

EFFECTS OF SOIL COMPACTION ON GROWTH AND YIELDS OF CROPS

It was reported by [52] that the ability of plant roots to penetrate soil is restricted as soil strength increases and ceases entirely at 2.5 MPa. [53] reported that as cone index approaches 2. 0 MPa and moves above this value, root growth has been shown to be restricted to varying degrees. Hence 2 MPa has been considered as a measure in the determination of soil hard pan layer [16]. [54]Further revealed that critical limit of penetration resistance restraining root distribution is within 40-50 cm soil depth and that subsoiling can reduce and provide increased rooting depth. [55], [56], [52], and [18]explained that hydrostatic pressure (turgor) within the elongating region of the root provides the force necessary to push the root cap and meristematic region through the resisting soil. If the hydrostatic pressure is not sufficient to overcome wall resistance and soil impedance, elongation of that particular root tip ceases. Plant roots constitute a major source of soil organic matter when decomposed; and while growing, are capable of both creating and stabilizing useful structural features.

[57] opined that excessive soil compaction impedes root growth and therefore limits the amount of soil explored by roots which in turn can decrease the plant's ability to take up nutrients and water, from the stand point of production. Plants grown in compacted soils have shown a smaller number of lateral roots than plants grown under controlled condition. Plants grown in more compacted soils showed smaller ratios of fresh to dry mass. Soil compaction can have adverse effect upon crops by - increasing the mechanical impedance to the growth of roots; altering the extent and configuration of the pore space and aggravating root diseases [12, 25-26, 29-32, 35, 58-68].

Plants grown in compacted soils have shown a smaller number of lateral roots than plants grown under controlled condition. Plants grown in more compacted soils showed smaller ratios of fresh to dry mass. Soil compaction can have adverse effect upon crops by – increasing the mechanical impedance to the growth of roots; altering the extent and configuration of the pore space and aggravating root diseases [12, 25-26, 29-33, 58, 60-62, 64-68].

[36] reported the effect of annual compaction (1987-1989) of 9 and 18 Mg axle loads, and subsoiling for a com/soybean rotation on a Hoytville silty clay loam (very poorly drained) soil. The effect on soil physical properties was also examined. It was revealed that the 9 Mg and 18 Mg loads significantly reduced yields through 1992 and 1994, respectively. According to the researchers, subsoiling generally improved yields of all treatments including control.

[68]Revealed that soil compaction caused yield reductions in cotton. Their study investigated the effect of soil compaction on canopy spectral reflectance, soil electrical conductivity (EC), and cotton yield. Field experiments were conducted during 2003-2005 using a completely randomized block design with four soil compaction treatments. The treatments were no subsoiling (control); subsoiled, disked, and bedded (conventional); subsoiled and compacted (compaction I); and compacted with no subsoiling (compaction II). These results verified that compaction affected canopy reflectance and reduced cotton yields. The practical implications of the outcome of this study are the potential use of EC and canopy reflectance to infer crop yield and extent of soil compaction.

Triticale and maize, with different structure of the root system and type of photosynthesis were examined to know changes in shoot physiology and root architecture in response to varying degree of soil compaction [66]. He reiterated that the effects of different levels of soil compaction (1.30, 1.47 and 1.58 Mg m^{-3}) on a shoot and root dry matter, leaf

number and area, number and length of seminal, seminal adventitious, nodal and lateral roots, leaf water potential (ψ), maximum quantum yield of PS II (Fv/Fm) and gas exchange were studied in the root-box. Severe soil compaction treatments decreased leaf number, leaf area and dry matter of shoots and roots, while increasing shoot-to-root dry matter ratio. In addition, high level of soil compaction strongly affected the length of seminal and seminal adventitious roots, and the number and length of lateral roots developed on the seminal root. Along with the restriction of root growth, significant influences were observed in ψ, Fv/Fm and gas exchange. High soil compaction treatments resulted in decreased ψ, Fv/Fm, and photosynthetic rate, transpiration rate and stomatal conductance for both triticale and maize. Maize whose root growth was more heavily restricted by the soil compaction compared to triticale showed greater damages in physiological characteristics in leaves, while the impact on triticale was relatively small. The results indicated that damages in photosynthesis, water relation and shoot growth by soil compaction would be closely related to sensitivity of root systems architecture to high mechanical impedance of soil.

[30] revealed a decrease in maize yield between 10.7 to 15.2% due to high soil compaction, when a study was carried out on the effects of different tillage regimes on soil compaction, maize seedling emergence and yields in eastern Argentinean Pampas region.

[25] carried out a research to evaluate soybean root development and grain yield under compacted soil, in an Oxisol. The experiment was arranged in a completely randomized design with six compaction levels and four replicates. The result showed that soil compaction decreased deep root development and did not affect root amount, but its distribution. Soybean yield decreased at the penetration resistance of 2.33 Mpa or higher, and soil bulk density of 1.51 Mg m^{-3} or higher.

PREVENTION AND ALLEVIATION OF SOIL COMPACTION

Precision traffic Agricultural Practice

This is a system of spacing all vehicle wheels to run between rows, minimizing the number of tracks, and then planting in the same row positions year after year. It follows that in precision traffic farming, traffic zones are separated from cropping zones in the field. This practice generally increases yield and improves timeliness of field operations. The firmly compacted traffic paths provide good traction and mobility. Precision traffic takes advantage of compaction, but does not eliminate it [38]. [69] measured soil physical properties on a Northwest Ohio farm where controlled traffic had been practiced in a ridge-till system for seven years on a Blount silt loam soil. He found that maintaining separate traffic zones and crop zones resulted in lower bulk density, higher air porosity, and higher air permeability beneath the crop rows compared to the traffic lanes.

Deep Tillage Practices

Deep tillage practices, normally referred to as subsoiling is aimed at restoring the lost soil properties and involves loosening compacted soil layers below the ploughing depth, without inverting them. Subsoiling leads to improved root growth and water and nutrient infiltration. It thus helps to reduce surface run-off and boost yields [64, 70]. They further stated that subsoiling creates significant effect on percentage of cone penetration decrease within depths of 10-20 cm and 20-50 cm.

Subsoilers, power tillers, tine cultivators and chisel ploughs are used in carrying out deep tillage practices to alleviate soil compaction [71-72]. [73] asserted that several types of subsoilers have been manufactured which adequately shatter the soil to break up compaction. Subsoiler shanks may be parabolic (curved) shaped or straight and with or without wings. In general the power required to pull a parabolic shank is less than a straight shank. The addition of wings to either parabolic or straight shanks increases the power requirement [31-33, 36 73-75].

Cultivating Cover Crops

[76] reported that deep-rooted cover crops may help alleviate effects of soil compaction, especially in no-till systems. Also planting cover crops such mucuna or velvet bean (*mucuna pruriens*) helps alleviate soil compaction. Thus as mucuna leaves fall to the ground, they form thick mat of biomass. This biomass conserves moisture and provides organic matter encouraging earthworm activities which reduces soil bulk density and adds nutrients to the soil surface, alleviating soil compaction and restoring soil fertility. The authors further stated that, cover crops in the Brassica (mustard) family provides a less expensive and less energy intensive alternative to tillage for alleviating the effects of subsoil compaction on agricultural soils. Winter cover crops with large taproots can alleviate the effects of soil compaction by penetrating the compacted layer when the soil is wet and relatively soft during the winter, leaving channels that enable water, air and cash crop roots to penetrate the soil profile more easily during the summer when the soil is dry and hard. This action has been dubbed "biological drilling." According to [12] there is a tremendous interest in conservational tillage systems and incorporation of cover crops into crop rotations to alleviate soil compaction.

Incorporating Organic Matter into the soil

[15] opined that decomposition of crop residues promotes stable soil structure. This material acts as a glue to hold soil aggregates together. Incorporation of organic manure into the soil is done by retaining previous crop residues on the soil

surface; growing small grains that have grass-like rooting systems; growing green manure crop in rotation; and applying animal manures, sludge, or other waste products. This strengthens soil structure, adds nutrients and organic carbon.

Practising mixed farming

Mixed farming helps to alleviate soil compaction. An area is cropped for some years (3 - 4 years) and left under pasture for two or more years before returning to it. Note that high animal stocking rates may cause compaction due to the trampling effect. Lighter stock rates and cut-and-carry feeding of animals in a feedlot in mixed farming can solve the problem.

Reduce secondary tillage

[15] revealed that decreasing the number of secondary tillage trips preserves the soil aggregates and decreases susceptibility to compaction. They further explained that 'overtilling' destroys the natural soil structure while continuing to decrease soil pore size. Each tillage operation breaks down soil aggregates and decreases the pore space necessary for good air and water flow. As a result, the soil becomes more susceptible to implement compaction and crusting.

Altering plough depth

An apparatus is provided for loosening highly compacted soil to a desired depth greater than 60 cm. A first trough of loosened soil is formed, then successive troughs are formed by pulling the disclosed plough in a pattern much like mouldboard ploughing.

CONCLUSION

This review work on engineering problems of soil compaction and their effects on growth and yields of crops has given us the impetus to reiterate that soil compaction is a well-established corpus of investigation generating over 3,000 referees in the last quarter century. Many aspects of the effects of soil compaction have been studied. Soil compaction occurs when soil particles are pressed together, leading to a reduction in the soil pore space. It is a process that brings about an increase in soil density or unit weight, accompanied by a decrease in air volume. Thus, when this happens, physical structure of the soil finds it difficult to support and applied weight or mechanical stress leading to a coarsening or lost of soil structural units, decrease in soil volume, increase in bulk density, decrease in porosity and reduction in hydraulic conductivity of the soil. Compacted soils have reduced available water capacity. The change in pore space restricts root growth, and the gas exchange necessary for plant growth. Compaction restricts infiltration of water, increasing runoff and erosion, leading to the loss of valuable nutrients.

Suggestions are hereby made as follows:

- Farmers are advised to carryout precision traffic agricultural practice and to avoid several passes of wheel traffic on agricultural land; more over planting of crops on soils with cone index of more than 1.5 kPa should be avoided.
- Deep tillage practices, normally referred to as subsoiling should be carried out on soils confirmed to be compacted. This is aimed at restoring the lost soil properties and involves loosening compacted soil layers below the ploughing depth, without inverting them. Subsoiling leads to improved root growth and water and nutrient infiltration.
- Farmers are advised to cultivate cover crops like mucuna and brassica which may help alleviate effects of soil compaction. Thus as mucuna leaves fall to the ground, they form thick mat of biomass. This biomass conserves moisture and provides organic matter encouraging earthworm activities which reduces soil bulk density and nutrients to the soil surface, alleviating soil compaction and restoring soil fertility.
- Incorporating Organic Matter into the soil promotes stable soil structure. This material acts as a glue to hold soil aggregates together. Incorporation of organic manure into the soil is done by retaining previous crop residues on the soil surface; growing small grains that have grass-like rooting systems; growing green manure crop in rotation; and applying animal manures, sludge, or other waste products. This strengthens soil structure, adds nutrients and organic carbon.
- Practising mixed farming helps to alleviate soil compaction. Thus, an area is cropped for some years (3 - 4 years) and left under pasture for two or more years before returning to it. Mixed farming helps to alleviate soil compaction

Finally, the problems of soil compaction are a global concern. As farmers continue to till the soil for the purpose of food production to meet the ever growing world population; the prevention and alleviation practices should be taken into consideration to avoid the negative effects of soil compaction.

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