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Soil Compaction Due to Increased Machinery Intensity in Agricultural Production: Its Main Causes, Effects and Management

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Abstract

In modern agriculture, most of the field operations from sowing to harvesting are done mechanically by using heavy agriculture machines. However, the loads from these heavy machines may induce stresses exceeding soil strength causing soil compaction. Nowadays, soil compaction is considered as a serious form of soil degradation, which may have serious economics and environmental consequences in world agriculture because of its effects on soil structure, plant growth and environmental events. Vehicle load, inflation pressure, number of passes, stress on the soil, and soil properties (e.g. soil water content, soil texture, soil strength, soil bulk density) play an important role on soil compaction. This chapter reviews the works related to soil compaction in agricultural areas. Also, it discusses the nature and causes of soil compaction, the effects of the compaction on soil properties, environment and plant growth, and the possible solutions suggested in the literature.

Keywords: soil compaction, soil degradation, soil properties, plant growth, controlled traffic

1. Introduction

In recent years, soil compaction has been considered as one of the most destructive environmental issues because it affects soil water dynamics, erosion, soil nitrogen and carbon cycling, cultivation energy requirement and effectiveness, pesticide leaching, and crop growth [1]. For example, the European Union has identified soil compaction as one of the main threats to soil that may cause the degradation of soils [2].

In simple terms, soil compaction can be described as the increase of bulk density or decrease in porosity of soil due to externally or internally applied loads. In agricultural production, soil compaction is considered as a complex problem in which soil, crops, weather and machinery interactions have an important role and which may result in dramatic economic and environmental problems. Wheel traffic from the use of heavy machinery and inappropriate soil management can cause the compaction of soil, creating impermeable layers within the soil that restrict water and nutrient cycles. This situation can result in reduced crop growth, yield and quality as well as a decline in the physical, chemical and biological indicators of soil quality such as destroyed soil structure, increased surface water run-off, soil erosion,

greenhouse gas emissions, decreased hydraulic conductivity, reduced groundwater recharge and a loss of biodiversity [3, 4].

Mainly, there are two types of soil compaction defined as surface soil compaction and subsurface compaction. Surface soil compaction is also called as soil crusting. This type of soil compaction happens when the surface soil aggregates are broken down through the impact of falling raindrops, runoff, standing water during irrigation, or tillage. Therefore, it restricts water and air entry into soil by causing runoff and erosion of soil and impedes seedling emergence. The subsurface compaction can be defined as tillage-induced compaction and wheel traffic-induced compaction depending on where it occurs. Tillage implements such as discs, moldboard plows and sweep type tools cause the tillage-induced compaction. This soil compaction type is mostly called as “hardpan,” or “plow pan” and occurs in the layer of soil just below the depth of tillage when soils are cultivated repeatedly at the same depth. Wheel traffic-induced compaction lies beneath the tillage zone and is caused by axle weight load to the soil. This type of soil compaction is the most difficult to eliminate, so prevention is important [4–7].

Until today, many scientists [3, 4, 8–13] have discussed the potential causes of compaction, its main consequences, and strategies to prevent and reduce soil compaction. Also, many field and laboratory studies have been conducted to better understand the mechanics of soil compaction, the factors affecting it and its effects on soil properties and crop growth in many parts of the world. Nawaz et al. [13] reviewed the main causes of the soil compaction, and its effects on soil physical, chemical, biogeochemical processes and biodiversity properties at both macro- and microscales. The authors also discussed the existing models for the soil compaction and proposed new directions for modeling the effects of the compaction on the soil properties. They emphasized that soil productivity was very important for human survival but any form of soil degradation can reduce the soil fertility and ultimately, it lowers the soil productivity. Also, it was underlined in the paper that in spite of hundreds of articles appearing during the last 10 years on the soil compaction, there was an urgent need to apply multidisciplinary approach in the soil compaction studies, addressing diverse effects in different soil compartments. Soane and van Ouwerkerk [14] summarized the studies carried out the impacts of soil compaction on the environment, including its effects on soil water dynamics, erosion, soil nitrogen and carbon cycling, cultivation energy requirement and effectiveness, pesticide leaching, and crop growth. They reported that compaction-induced changes could lead to soil degradation, pollution of the atmosphere and of ground and surface waters, and might increase the mechanical resistance of the soil, resulting in an increase in soil cutting force, fuel consumption, working hours, and abrasion of agricultural instruments. Also, several researchers [15–18] reported that soil compaction negatively influenced the water dynamics, pesticide diffusion, soil erosion, carbon and nitrogen cycle, plant growth, and mechanical operations cost. Although overall effect of the soil compaction on environment, soil properties and the plant yield is mostly reported as negative, moderate compaction can sometimes result in yield increase by increasing the contact between the roots and soil particles which may lead to the rapid exchange of ions between the soil matrix and roots [13]. Batey and McKenzie [19] stated that the effects of soil compaction on crops and soil properties are very complex and should be well documented. Therefore, it is very important to understand what are the causes and harmful level of soil compaction, how soil compaction affects soil properties and plant growth, and to know how to avoid soil compaction as much as possible in agricultural production.

This chapter includes identification of compaction, the main causes of soil compaction in agricultural fields, its effects on soil properties, environment and plant growth, and strategies for preventing compaction in agricultural production.

2. Soil compaction and the main causes of soil compaction in agricultural fields

Soil compaction is defined as the increase of bulk density or decrease in porosity of soil due to externally or internally applied loads. Soil compaction can be identified either in the field, the laboratory or via remote sensing. In field, soil compaction can be detected by observing or measuring the changes in soil structure, soil moisture and soil color, penetrometer resistance, permeability to air or water, waterlogging on the surface or in subsurface layers, and crop or root growth properties [20]. In Laboratory, soil bulk density, pore-size distribution, water permeability and the relative apparent gas diffusion coefficient is measured to determine the permeability of soils to air and water and therefore on the degree of compaction. Also, remote sensing techniques helps to recognize alterations of soil structure, root growth, water storage capacities and biological activity [21].

Soil compaction in agricultural fields is commonly known to be caused by several forces (natural and man-induced) such as raindrop or tillage equipment during soil cultivation, or trampling of livestock animal or from the heavy weight of field equipment such as mostly tractors, heavy cultivation machinery, harvesting equipment [3, 18]. In this case, we can say that high mechanical load, less crop diversification, intensive grazing, low organic matter and tillage at high moisture contents can lead to soil compaction. Shah et al. [12] summarized the main causes of soil compaction as shown in **Figure 1**. Similarly, Ziyadeh and Roshan [22] conducted a survey to study the causes of soil compaction problems. They defined common causes of soil compaction as natural processes, earlier planting schedules, overgrazing and animal trampling which directly affect the penetration resistance, besides, increased machinery weight and intensity, and especially excessive tillage at high soil moisture content.

Raindrop is one of the natural causes of surface compaction, and it causes a soil crust (usually less than 1/2 inch thick at the soil surface) that may prevent seedling emergence. This soil crusts reduces water infiltration and increases surface runoff, and thereby sediment and nutrient losses [6, 23].

Using tillage implements at the same depth can cause serious tillage pans or hardpans just below the depth of tillage. This tillage pan, which is generally relatively thin (2,5 to 5 cm), can reduce yield potential by restricting root growth and nutrient uptake of plant in soil [24].

Trafficking by the tyres of heavy farm machines is known to be the major cause of soil compaction in agricultural fields. Soil compaction by wheels is characterized by a decrease in soil porosity localized in the zone beneath the wheel and rut formation at the soil surface [18]. The degree of soil compaction by farm machines depends on not only the characteristics of the agricultural machinery but also the soil properties such as soil moisture, soil type, texture, structure, and moisture [3, 8, 25]. Several researchers [26–28] showed that the compaction rate depended on the soil characteristics, and the weight, the pressure and the vibrations of the agricultural machinery. Different machines, or even the same machines with different tyres, differ in their loading and pressure on the soil [25, 26]. Nawaz et al. [13] reported that the soil compaction by a machine depended on the soil strength which is influenced by the organic matter, water content, soil structure, and texture, and machine properties expressed by axle load, number of tyres, tyre dimensions, tyre velocity, and soil-tyre interaction. Botta et al. [29] reported that tyre sizes and rut depth/tyre width ratio had significant effect on soil compaction. The researchers emphasized that the farmer should pay attention to the axle load, the tyre size and the soil water content at the traffic moment. Also, the size, the inflation and the shape of tire in addition of the tyre's load have significant effects on the ground pressure, indicating traffic-induced soil compaction [30, 31]. Håkansson and Reeder [32] found that the

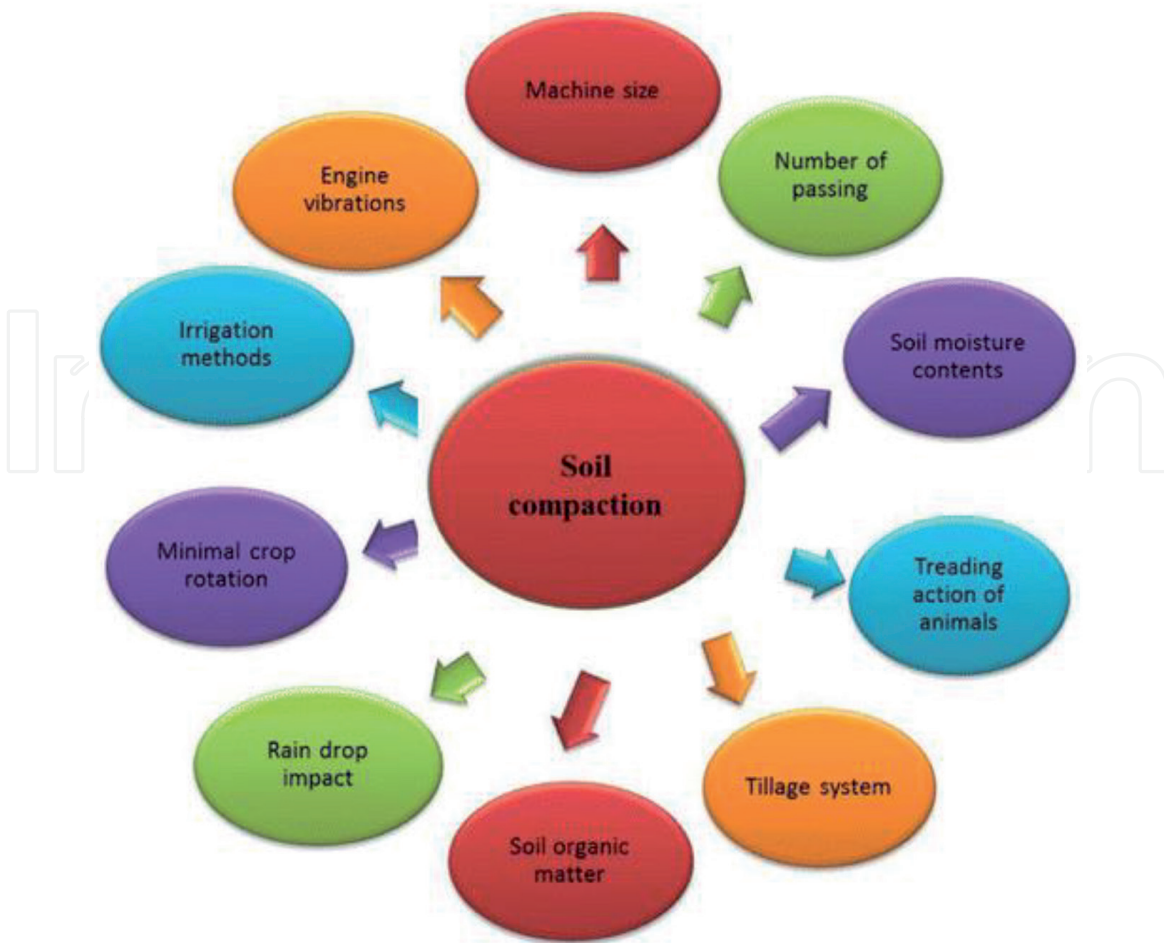


Figure 1.
A summary of the main causes of soil compaction in agriculture fields [12].

vehicles with high axle loads generally caused deep subsoil compaction when trafficked on soils with high moisture contents, and this deep subsoil compaction caused persistent and possibly permanent reductions in crop yields. Soil moisture and axle load causes soil compaction at various depth as shown in **Figure 2**. It is seen in **Figure 2** that high axle load could result in soil compaction to deeper depth. Also, at a given load and tire size, increasing soil moisture content causes much deeper compaction than dry [33]. Da Silva et al. [34] stated that high contact pressures applied to soil, which is described as the ratio of mass of each machine's axle and the contact area of the run, resulted in a greater degree of compaction, in addition to promoting other negative effects. The researchers underlined that it was possible to minimize the effects of soil compaction through the appropriate contact pressure of agricultural machines. They suggested that the use of new technologies and suitable management practices should develop and adopt to characterize machine size and solve the machine-soil problems, especially about the distribution of pressures caused by the wheels in the soil, thus avoiding the negative effects of compression. Similarly, Porterfield and Carpenter [35] stated that high-pressure tire-ground contact caused an increase in the density of the soil. so, the researchers recommended to keep contact pressure low to avoid compaction. The intensity of trafficking, also referred to as the number of passes of agricultural machinery on the soil throughout the life of the crop in addition to the wheel ground contact pressure and absolute wheel load, has a significant effect on the degree of compaction and the depth to which wheel pressure affects the soil [36]. Zhang et al. [37] stated that the increased frequency of passes associated with the small four-wheel tractors, which is smaller mass and lower ground pressure than the medium power tractor, potentially was more detrimental

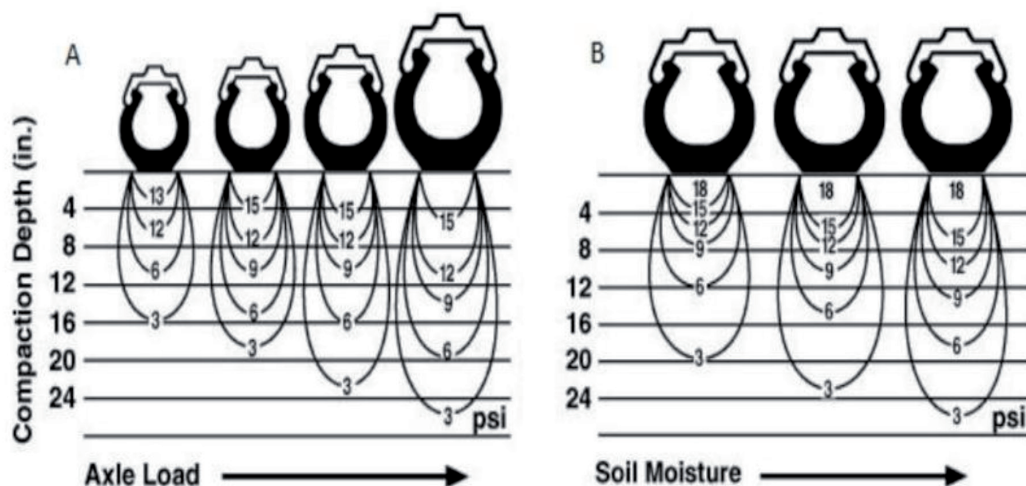


Figure 2.
 (A) The effect of axle load on soil compaction depth, (B) The effect of soil moisture content on compaction depth [33].

than those associated with the medium power tractor. Rusanov [38], who reported official standard values of maximum permissible normal stress at a depth of 0.5 m, observed traffic intensity mostly resulted in higher soil stress than the allowable stress in subsoil. Similarly, Botta et al. [39] observed that high traffic frequency (10 and 12 tractor passes in the same tracks) of a light tractor on typical Argiudol soil produced a significant increase in cone index and dry bulk density in the topsoil and subsoil levels. However, Hamza and Anderson [18] reported that the first pass of a wheel was known to cause a major portion of the total soil compaction and subsoil compaction may be induced by repeated traffic with low axle load and the effects can persist for a very long time. In summary, we can say that repeated passes of agricultural machinery at the same locations will increase soil compaction. Also, Shah et al. [12] emphasized that in intensive agriculture, high axle load of heavy tractors and field machines resulted in compacted soil layer, damaging the structure of tilled soil and subsoil and reducing crop and soil productivity. Keller et al. [40], who analyzed the effect of the increase in weight of agricultural vehicles on soil stress and soil bulk density, showed that the increase in machinery weight has resulted in an increase in subsoil compaction levels, and highlighted that future agricultural operations should consider the inherent mechanical limit of soil.

Soil properties (soil texture, soil aggregate properties, moisture content, organic matter content) and frequent use of chemical fertilizers has significant effect on soil compaction [8, 18]. It is mostly stated that the depth to which compressive forces are transmitted depends on the moisture content in soil profile. Batey [3] described the relationship between soil moisture content and compressibility as following: When the soil was dry and firm throughout the profile, there might be no significant compaction effect. However, when the surface layers were moist and soft lying over dry soil, the upper layers might be strongly compressed, and when the surface layers were dry and firm with moist soil below, the compression might be transmitted some way downwards to compress the moister vulnerable soil. Gysi et al. [41] determined that soil moisture content and wheel load significantly influenced the bulk density at a depth of 0.12–0.17 m. The researchers stated that a soil with very low moisture content was less vulnerable to compaction than a soil with high moisture content. The texture, organic matter content, aggregation stability and mineralogy of the soil also have a significant effect on compressibility of a soil by agricultural vehicles. Several researchers [13, 18] stated that soil texture was one of the most important factors in determining the susceptibility of a soil to compaction. Horn and Lebert [42] reported

that coarse-textured soils were less susceptible to compaction than those with a fine texture. Moreover, Horn et al. [15] found that the silt loam soils with low colloid contents were more susceptible than medium or fine textured loamy and clayey soils at low water contents while the sandy soils were slightly susceptible to the soil compaction. Soil aggregation and organic matter content are also the most influencing factors that makes soil resistance to compaction [13, 43]. Ellies Sch et al. [44] reported that soils with poor structure and aggregation were extremely vulnerable to the impacts of wheel traffic, while susceptibility to compaction could be reduced with an increase in soil aggregation. Also, soil organic matter is a very important soil property, which can determine the magnitude of soil compaction. The amount of organic matter in soil significantly influence the compressibility degree under axle load of vehicles [13]. Previous works [45–47] has shown that increasing organic matter in soil may reduce compatibility by increasing resistance to deformation and/or by increasing elasticity.

3. The effects of soil compaction on soil properties, environment and plant growth

Soil compaction alters the soil structure and hydrology by changing many aspects of the soil such as strength, gas, water and heat, which affect chemical and biological balances. In turns, all these alterations in the soil influence root and shoot growth and consequently crop production and environmental quality **Table 1** [58]. presents a summary of studies related to the effects of soil compaction on soil, environment and plant growth. In most of these studies, the subsoil compaction negatively affected soil physical conditions, which substantially decreased crop yield. However, some studies [50, 56] showed that moderate compaction had no effect on crop yield or can increase yield. Also, Gürsoy and Türk [59] stated that moderate soil compaction in agriculture production was needed to get good seed/root-soil contact, suitable soil density, timely emergence of seed, root growth and the ability of the plant to absorb the moisture and nutrients from soil.

In Global Land Outlook Working Paper expressed by [60], the consequences regarding the effects of soil compaction on soil properties, environment and crop plant's morphological and physiological growth have been presented as seen in **Figure 3**. Also, Horn et al. [15], who summarize the works carried out about effects of soil compaction on the structure of arable soils, stated that soil compaction caused by traffic of heavy vehicles and machinery resulted in soil structure deterioration, both in the topsoil and in the subsoil. They reported that owing to dynamic loading, soil physical properties such as pore size distribution and pore continuity were negatively affected, which entails decrease in air and water permeability and resulted in increased soil strength. The researchers emphasized that these changes in soil structure may have a negative effect on the soil biota, on physical–chemical equilibria and redox potential, on the soil's filtering and buffering capacity, on ground water recharge and, finally, on crop yield.

The major effect of soil compaction on soil properties is known as increase in soil bulk density and decrease in total porosity as soil aggregates are pressed closer together, resulting in a greater mass per unit volume and less space for air and water in the soil [15]. Changes in the soil pore system due to compaction can adversely affect key soil hydraulic properties and aeration such as saturated hydraulic conductivity and air movement in soil [58]. Ziyadeh and Roshan [22] stated that pore space provided a room for air and water to circulate around the mineral particles, providing a healthy environment for plant roots and beneficial microorganisms, however, in compacted soils, the particles were pressed together so tightly that the space for air and water was greatly reduced. The researchers emphasized that lack of pore space resulted in

| Land vehicles traffic | Place | Soil texture | Major findings | Reference |
|---|---------------------|--|---|-----------|
| Different passes of a tractor pulling a trailer, during harvest operations | Argentina | A fine clay | The first pass of the tractor (4200 kg) resulted in a reduction of grass yield (40.3%) in comparison with the control (no traffic) treatment | [48] |
| Weighted tractor compaction and a control of no compaction. | Scotland England | An imperfectly drained silty clay loam and a well drained sandy loam | Damage to soil structure through compaction reduced the yields of grassland swards by mechanical (tractor) compaction (14.5% reduction) after three years of these treatments. The soil type had significant effect on yield losses | [49] |
| Most trafficked rows and least trafficked rows | USA | Loamy soils, fine sandy loam soils and fine sands | Different crops grown in a no till field were not very much influenced by wheel traffic | [50] |
| Additional load (4.40, 6.40 and 8.40 kg) on the tractor rear wheel and 1, 6, 11 and 16 passes | India | Sandy loam soil | Yields of wheat decreased with an increase in the number of passes/trips at all load and pass combinations. | [51] |
| Wheel loads (3, 8 and 12 Mg) and single and multiple (4–5) wheel passes | Denmark | Sandy loam soil | High wheel loads caused significant subsoil compaction at >50 cm depth and heavy traffic in dense soils created a potentially restrictive subsoil structure for plant growth | [52] |
| Axle loads of sugarbeet harvesters and the number of passes | Sweden | Loam soil Sandy loam soil Sand soil | Heavy traffic during harvest of sugarbeet implied a major risk for compaction of the subsoil, which can be seen as a long-term threat to soil productivity. | [53] |
| The number of passes of 7.0 t roller having length of 1.5 m and diameter of 1.22 m | Pakistan | Well-drained alluvial silt loam | The subsoil compaction adversely affected soil physical conditions, which substantially decreased the yield of wheat. | [54] |
| Axle load (0, 7 and 17 tons) | Jordan | Clay loam soil | The yield was significantly reduced as a result of compacting loads. | [55] |
| No-tillage system, the tractor traffic, harvester traffic and soil chiseling management | Brazil | Oxisol soil | Soybean grain yield was reduced due to both soil chiseling and heavy traffic by harvester | [56] |
| Harvester traffic intensities under direct sowing | Argentina | Fine clay soil | A higher axle load than 79.70 kN caused the cone index peaked in the subsoil to depths below 35 cm and significantly reduced soybean yields. | [57] |

Table 1.
Effects of soil compaction on soil, environment and plant growth.

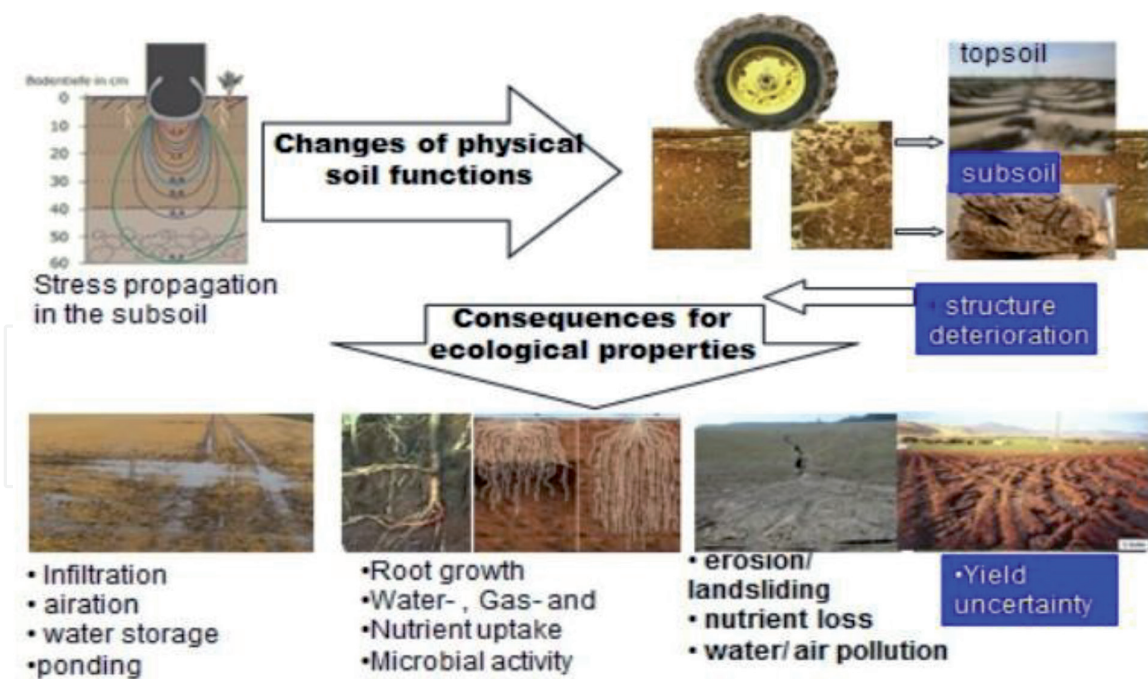


Figure 3.

The consequences of soil compaction regarded with soil, environment and plant growth [60].

the lack of oxygen, which is very important for plant growth, decomposing organic matter, recycling nutrients and aerating the soil. In addition to soil bulk density and porosity, penetration resistance significantly affects plant root growth and crop yield. The previous works [61–64] showed that plant root growth could be slowed down or completely impeded at penetration resistance values of 2 and 3 MPa, respectively. Also, the soil physical properties changed due to soil compaction can alter elements mobility, change nitrogen and carbon cycles and soil biodiversity [13].

Effects of soil compaction on plant growth are complex and depended on many factors. Mainly, it is known that high soil penetration resistance and low oxygen concentration in a compacted soil can reduce crop yield due to decreased root elongation rates and thus limited accessibility to water and nutrients [65]. Also, plants in compacted soils can also suffer from water stress due to reducing water infiltration and increasing runoff [15]. Keller et al. [40] discussed in detail how soil compaction changed soil properties, and how the soil properties changed by soil compaction affected plant growth and environment. They highlighted that soil compaction was one of the main causes of the yield decrease observed for major crops in many European countries. In an experiment with barley, Willatt [61] observed that root length density in the upper 0.30 m of soil and rooting depth decreased as the number of tractor passes increased from zero to six. Ishaq et al. [66], who study subsoil compaction effects on root growth, nutrient uptake and chemical composition of wheat and sorghum, determined that root length density of wheat below 0.15 m depth was significantly reduced with increased soil bulk density. They recommended that appropriate measures such as periodic chiseling, controlled traffic, conservation tillage, and incorporating of crops with deep tap root system in rotation cycle should be applied to minimize the risks of subsoil compaction. de Moraes [56], who study the impact of soil compaction on soybean root growth, investigated three soil compaction levels (no-tillage system, areas trafficked by a tractor, and trafficked by a harvester) and soil chiseling management (performed in an area previously cultivated under no-tillage) on soil properties and plant root growth. The researchers observed that root growth was influenced by soil physical conditions during the cropping season and soybean grain yield was reduced due to both compaction (caused by harvester traffic) and excessive loosening (promoted by chiseling)

compared the no-tillage system. Obour and Ugarte [67] used a meta-analytical approach to summarize the results from 51 published articles on the impacts of soil compaction attributed to machinery axle load, wheel passes, compaction events and tire inflation pressure on soil bulk density, degree of compactness, penetration resistance, volume of water filled pores at field capacity, air permeability at field capacity, saturated hydraulic conductivity, and grain yield of corn, wheat, barley and soybean. Results from this meta-analysis showed that compaction increased the soil mechanical strength affected by increased soil bulk density, degree of compactness, penetration resistance. Also, compaction decreased hydraulic conductivity characterized by air permeability and saturated hydraulic conductivity from the topsoil down to the subsoil (>40 cm depth), and grain yield of corn, wheat, barley, and soybean. The researchers suggested that soil hydraulic properties might be more sensitive indicators to reflect the impact of soil compaction on soil structure and pore system functions in the soil profile. Also, negative effects of soil compaction on plant root growth and crop yield have been recognized by several researchers [26, 38, 64].

Soil compaction can affect crop yield depending on soil texture and growing season precipitation. Voorhees [5], who presents relative barley grain yield as a function of the degree of compactness of a clay soil in Sweden, reported the effect of soil compaction on grain yield depending on climate change as following: 1) During relatively dry climatic conditions, grain yields were increased by almost 40% with the initial increases in degree of compactness. However, when the degree of compactness approached 90, yields decreased significantly. 2) Similar results were obtained during a normal year but less pronounced. 3) During a wet year, yields decreased with any increase in degree of compactness above 75. The researcher stated that plants could tolerate (might even need) a more highly compacted soil during dry conditions than during wet conditions.

In summary, soil compaction can significantly change the physical, chemical and biological properties of soil depending on climate and initial soil properties such as soil texture, structure, moisture content, organic matter content. These changes in soil properties can have significant effect on the penetration of plant roots, their growth, soil-plant-water relations, the ability of plants to take up nutrients from soil and consequently crop yield. In another sense, the effect of the same compaction degree on plant root growth and yield depends on the crop grown, soil structure, and weather conditions. All literature data shows that the effects of soil compaction on root and plant growth have a complex interaction including many soil, climate and plant properties. This complex interaction requires complex hypotheses to explain the effects of soil, climate and plant properties on root and plant growth.

4. Strategies for avoiding and reducing soil compaction

Many strategies have been used to avoid soil compaction in agricultural fields and to ameliorate compacted soil or alleviate its associated stresses. Strategies can be roughly divided into three groups: measurements to avoid further compaction, remedial treatments, and methods to alleviate soil compaction [33, 68].

The best way to manage soil compaction is to prevent it from happening. This includes reducing axle load, proper inflation and size of tires, minimizing soil tillage, increasing stability of soil structure and conducting field operations at appropriate soil moisture content [6]. The capacity of the soil to resist stress (i.e. the strength against compression) and loading of machine is considered to be the major factors affecting the soil compaction by farm machineries [11]. The soil strength against compression is influenced by the organic matter, water content, soil structure, and texture. Therefore, improving soil structural stability and

aggregate can reduce the risk of soil compaction [13]. Soil structural stability and aggregate can be improved by increasing soil organic matter content and reducing stress on the soil due to machinery traffic. This can be achieved by using conservation tillage systems [11]. Similarly, several researchers reported that long-term use of conservation tillage systems resulted in lower soil compaction threat because it increased surface organic matter contents, more stable soil structure, and increased hydraulic conductivity due to worm holes and stable biochannels [63, 69]. Loading of machine on soil is expressed by axle load, number of tyres, tyre dimensions, tyre velocity, and soil tyre interaction [13]. The axle load and the contact pressure of tires is known to be the most important parameters affecting soil compaction. A high wheel load may lead to compaction of soil in both the top and deep sublayers, whereas low axle loads will cause compaction in the topsoil and the upper part of the subsoil only. An axle load or wheel loads describe the weight distribution of machines, depending on the degree of the loading of tank or weight transfer during plowing. Therefore, the weight distribution may vary markedly between wheels on the same axle. In their literature review, Alakkuku et al. [11] recommended single axle load of 4–6 Mg for moist mineral soils to avoid soil compaction below normal primary tillage depth (0.2–0.3 m) and a limit of 8–10 Mg for tandem axle loads on moist soils. The researchers stated that to reduce axle loads, machine weight may be reduced by using new, lighter materials or multiple axles can be used to spread the load. Also, they reported that wheel load should be linked with soil contact pressure recommendations because the wheel load alone does not give any information about the stress level transferred to the soil and the corresponding stress distribution in the soil. Contact area between the wheel and soil and the basic dimensions of wheel such as width and length has significant effect on soil contact pressure of wheel [11]. Also, ten Damme et al. [70] stated that the stress distribution in the contact area between the tyre and the soil is of primary importance for the propagation of stress in the soil. The researchers indicated that tyre design might further help reduce the risk of soil compaction at a specific load if it allows for further reductions of the tyre inflation pressure. This literature findings shows that soil compaction can be avoided by adjusting tire size and tire inflation pressure, or using rubber-belt tracks [11, 71]. Alakkuku et al. [11] stated that low tyre inflation pressure usually provided low ground contact pressure and allowed even pressure distribution, which are advantageous to both soil compaction caused by wheel traffic and to wheel tractive efficiency.

According to our review conclusion, we can say that the wheel load and the soil contact pressure is the major engineering tools for the control of subsoil compaction and to avoid permanent subsoil compaction, the machines and equipment used on the critical field conditions should not cause higher stress than the bearing capacity (strength) of soils. Also, the compaction risk in given vehicle–soil interactions might be quantitatively estimated by using pre-consolidation stress as an indicator of the bearing capacity of a soil. Alakkuku et al. [11], who reviewed technical choices to minimize the risk of subsoil compaction, presented a framework of machinery–soil system in connection with subsoil compaction as shown in **Figure 4**. The researchers stated that to prevent subsoil compaction, recommendations for wheel load–ground contact pressure combinations should be made available for different soil conditions. Chamen et al. [69], who discussed the machinery usage during field practices to avoid subsoil compaction, stated that the bearing capacity of soils would be improved by increasing their structural stability, such as may be achieved with reduced or no tillage systems. The researchers summarized the preventative strategies suggested for the avoidance of subsoil compaction as follows: (1) no repeated soil loosening as a routine cultivation technique, (2) increased

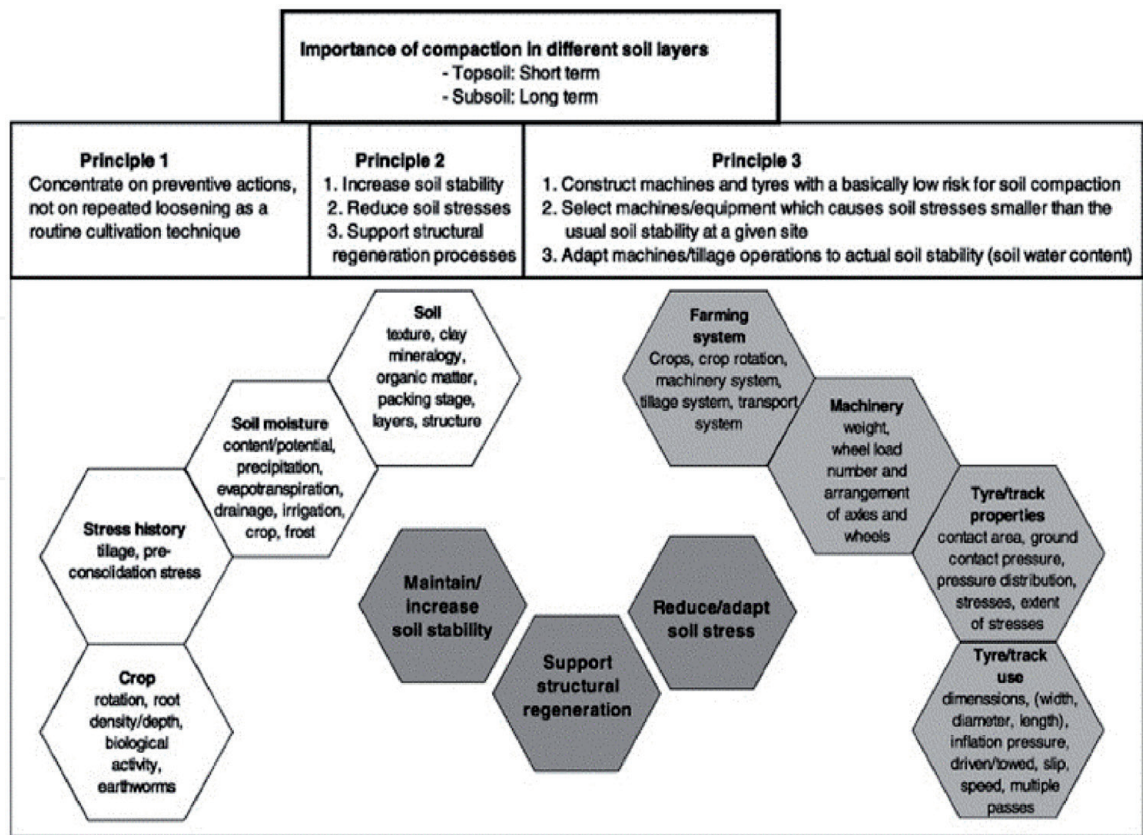


Figure 4.
A framework of machinery–soil system in connection with subsoil compaction [11].

soil stability and reduced soil stress, (3) the selection of machines and field practices with a low risk potential, (4) the assimilation of new, low risk technologies. Also, Kumar et al. [72] stated that the management of soil compaction might be achieved through suitable application of some or all of the following techniques: (1) decreasing the pressure on soil either by reducing axle load or increasing the contact area of wheels, (2) conducting field operations at optimal soil moisture content, (3) decreasing the number of passes of farm machinery and the intensity, (4) restraining traffic to certain areas of the field or controlled traffic, (5) improving soil organic matter through retaining of crop and pasture residues, (6) eliminating soil compaction by deep ripping in the presence of an aggregating agent, (7) including the plants with deep, strong taproots in crop rotations.

In this case, we can suggest the following solutions to prevent and alleviate soil compaction and its detrimental effects:

1. Maintaining an adequate amount of organic matter such as stubble retention, green and brown manure or addition of plant or animal organic matter from external sources in the soil stabilizes soil structure and makes it more resistant to compaction because it acts a buffer preventing or lessening transmission of compaction to subsoil from external loads acting on the earth [18].
2. Controlled traffic farming, which confines all machinery loads to the least possible area of permanent traffic lanes, was recommended by many researchers [73] to reduce the damage to soils caused by heavy or repeated agricultural machinery passes on the land. By controlling traffic, the tracked area will have a slightly deeper compaction but the soil between the tracks will not be compacted. Controlled traffic systems has been stated to have fundamental advantages in maintaining 'good' soil structural conditions of non-trafficked crop beds.

3. Another strategy for managing compaction is properly to decrease the contact pressure of tires and axle loads. Therefore, the machines and equipment used on the field in critical conditions should be adjusted to actual strength of the subsoil by controlling wheel/track loads and using low tyre inflation pressures [11]. Other methods to reduce compaction include the use of dual wheels, rubber tracks and flotation tyres.
4. The conservation agriculture techniques can be practiced to reduce traffic on the soil. A conservation tillage system can reduce the need for vehicle traffic in the field because there are fewer needs for tillage or cultivation operations [74].
5. Subsoiling/chiseling can be used for eliminating soil compaction, destroying hard pans and ameliorating hard setting soils developed due to traffic and puddling. Deep ripping of compacted soil may also improve soil health and ability of plants to resist disease [75].
6. Incorporating crops and pasture plants with strong tap roots able to penetrate and break down compacted soils in the rotation is desirable to minimize the risks of subsoil compaction [56].
7. Field operations should not be performed under wet soil conditions. Soil is more compressible at wet soil conditions. Traffic during high moisture conditions may compact soil, whereas the same traffic under dry conditions will not [18].

5. Conclusions

In recent years, the structural and technological development of modern agriculture caused a significant increase in the power, size and the weight of vehicles and machinery used on agricultural fields. This dramatic increase in the weight of agricultural machinery and the necessity to use heavy machines in unfavorable soil conditions have caused a significant increase in the subsoil compaction, which is considered as a serious form of soil degradation and may have serious economics and environmental consequences in world agriculture. The main results of our literature evaluation showed that severe soil compaction might result in a decreased root growth and plant development, and consequently, a reduction in crop yield because it adversely affect key soil hydraulic and aeration properties such as saturated hydraulic conductivity and air movement in soil. Soil compaction is also an environmental problem because it is one of the causes of erosion and flooding. In addition, it directly or indirectly increases nutrient and pesticide leaching to the groundwater and nitrous oxide emissions to the atmosphere. Therefore, prevention of soil compaction and alleviation of existing compaction is one of the most important issues in agricultural production in order to sustain or improve soil fertility and productivity.

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