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REVIEW ARTICLE

Soil compaction effects on soil health and crop productivity: an overview

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Abstract Soil compaction causes substantial reduction in agriculture productivity and has always been of great distress for farmers. Intensive agriculture seems to be more crucial in causing compaction. High mechanical load, less crop diversification, intensive grazing, and irrigation methods lead to soil compaction. It is further exasperated when these factors are accompanied with low organic matter, animal trampling, engine vibrations, and tillage at high moisture contents. Soil compaction increases soil bulk density and soil strength, while decreases porosity, aggregate stability index, soil hydraulic conductivity, and nutrient availability, thus reduces soil health. Consequently, it lowers crop performance via stunted aboveground growth coupled with reduced root growth. This paper reviews the potential causes of compaction and its consequences that have been published in last two decades. Various morphological and physiological alterations in plant as result of soil compaction have also been discussed in this review.

Keywords Land degradation · Soil compaction · Soil health · Soil harness · Tillage · Root growth · Stomatal conductance

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Introduction

Bourgeoning population and economic development are continuing to put a great challenge and pressure on land use particularly in developing countries. In addition, worldwide intensive agriculture has been preferably employed involving shorter crop rotations, mono cropping system over seasons, and heavy machinery use with a purpose to increase net profit in short time (Poesse 1992). Intensive cultivation involves heavy cultivation of crops and over exploitation of soil, could be more worsen when heavy tillage is employed to manipulate soil conditions. Tillage operation consisted of primary tillage and secondary tillage, employed to increase the soil's structural macroporosity, while excessive tillage operations over these freshly tilled soils cause soil compaction (Wang et al. 2004). Raghavan et al. (1992) reported that soil compaction causes reduction in soil porosity with concomitant increase in soil bulk density. It is also coupled with decline in hydraulic conductivity of soil and development of hard crust below the tilled layer, smeared layer (Soane et al. 1981).

With time, research on farming systems deducted improved tillage practices under conventional and conservation tillage practices, to cope with the new pressures associated with intensive agriculture, which would otherwise deteriorate soil structure to an extent that crop yields might affect significantly. Tillage operations are done by using heavy machines with high axle load, wheel slip, and ground pressure thus impinges on soil physical properties (Arshad et al. 1999; Wang et al. 2004). Conventional tillage relied on heavy soil opening and non-site specific wheeling result in reduction of macropores led to soil hardening under tilled layer. Furthermore, Botta et al. (2007) examined the penetrating response of roots in soils with high bulk density and referred compaction as a cause of reduction in soil porosity. Alteration in pore size distribution led to unstable consolidation of soil particles as a response of soil compaction (Mapa et al. 1986). Formation of macropores in soil could be affected by different interculture operations, cropping system, and/or field trafficking. Nonetheless, conventional tillage also results in the formation of high macropores, which could be associated with excessive soil loosening. Furthermore, Petelakau and Dannowski (1990) reviewed that frequent heavy traffic disintegrated the structures of both top and subsoil especially on arable land. This was supported by Bottam et al. (2004), who examined the effect of repeated traffic over same track, resulted in subsoil compaction and significant yield reduction of soybean (*Glycine max* L.).

Effects of soil degradation particularly of soil compaction are now well documented related with much detrimental and wider impact as merely on the growth and yield of the crop in question. Nature and extent of this degradation can be embellished by the lack of organic matter. It also affects soil organic carbon and nitrogen mineralization, concentration of carbon dioxide in the soil (Conlin and Driessche 2000), and volume of macropores in the soil (Barnes et al. 1971; Taylor and Brar 1991) and hampers root proliferation in soil, as affected by enlarged mechanical resistance or poor aeration (Chan et al. 2006). The effects of soil compaction on crops and soil properties are complex and well documented (Batey 1990). This review shows causes of soil compaction with concomitant effects on soil health and crop performance. Current climate change also results in release of greenhouse gas emissions by altering carbon sequestration or nitrogen mineralization. We also attempt to discuss the current knowledge about greenhouse gas emission in compacted soils.

Causes and linkages of soil compaction

Efforts have been made to quantify the effects of soil compaction and to analyze spatial and temporal relationship between extent of compaction and its causes. This section demonstrates key components responsible for soil compaction (Fig. 1). Key components such as mechanical load, soil physical properties, agronomic operations, and crop rotation can influence soil compaction (Hettiaratchi 1987; Hamza and Anderson 2005).

1. Mechanical load

Most agricultural operations required the use of heavy machinery during tillage and interculture or fertilizer application (Tullberg 1990). The continuous increases in the weight of farm machinery and the necessity to use heavy machines have

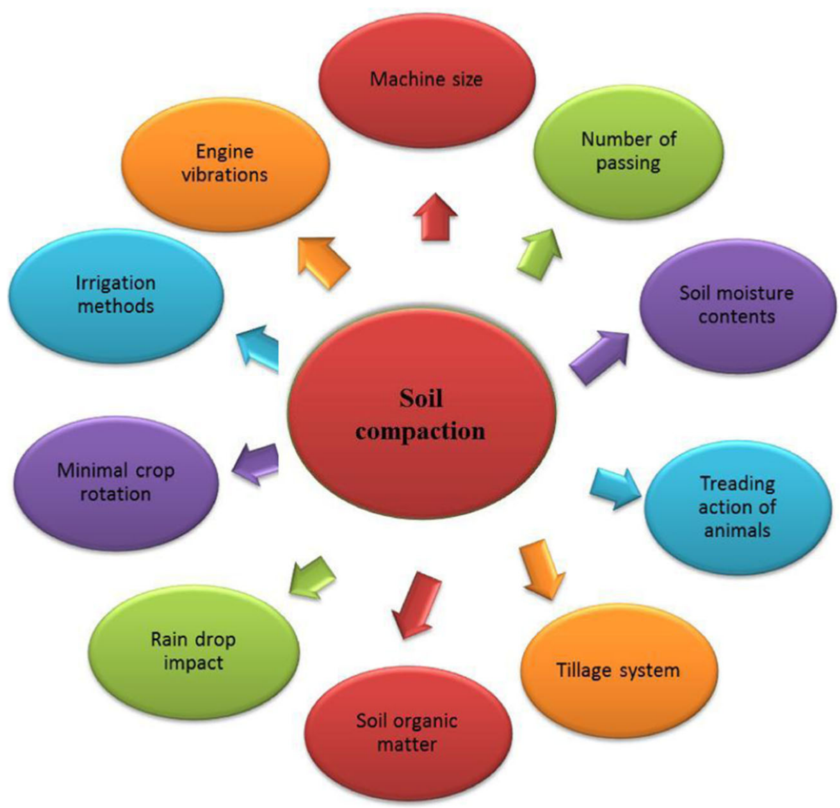

Fig. 1 Summary of factors inducing soil compaction

increased the subsoil damage. Mechanically caused soil compaction is well accepted and documented, characterized by reduction of crop growth and deterioration in soil quality in many parts of the world (Bennie and Krynauw 1985; Soane and Van Ouwerkerk 1994; Smith et al. 1997). However, the vulnerability of soil to become compacted has been observed as an interaction of numerous factors, including soil physical properties, wheeling, number of passing and farming practices (Smith et al. 1997; Hamza and Anderson 2005), structure of tilled soil layer after wheeling (Horn et al. 1994), soil water status (Gue'rif 1984), and short and limited crop rotations with high intensity of strip cropping and drop in humus content due to increased mineralization and reduced humification. The nature and degree of traffic-induced compaction is influenced by traffic; Jorajuria et al. (1997) documented his findings and suggested that most dramatic compaction was developed in the field as a result of irregular traffic over soil surface especially when soil was wet, while control (unplowed land) pertained smallest penetrometer resistance throughout the profile in comparison to any other trafficked field. An unplanned and irregular heavy wheeling over field caused rutted soil surface and compacted soil spot on different field places (Li HongWen et al. 2000).

Machine size, axle load, and engine vibrations The extent and nature of soil compaction is influenced by the size of machine/traffic employed. Increasing the size of agricultural implements and development of multipurpose machines such as combine harvester could be a significant cause of soil compaction and deterioration. Though such multipurpose machines save time and energy, high axle load and other heavy parts of such machines induced high pressure to the ground (Van den Akker and Stuiver 1989). In a study, Håkansson and Petelkau (1994) compared the wheel weight, size, and axle load of various farm implements and concluded that combined harvester, slurry tankers, and six-row propelled sugar beet harvester with three axles, having weight more than 25, 30, and 50 mg, inserted significant amount of pressure on soil, thus are potential source of soil compaction.

Since it is well documented in literature that axle load has astonishing impacts in the development of soil compaction with concomitant reduction in crop performance. Ground contact pressure can be determined by axle load divided by the surface area of contact between machine and soil. Ground pressure explains/causes top soil compaction, while high axle load leads to subsoil compaction (Botta et al. 1999). In intensive agriculture, soil becomes compacted as a result of high axle load, damaging the structure of tilled soil and subsoil and reducing crop and soil productivity (Defossez and Richard 2002). In fields, where machines with heavy axle loads are employed, compacted soil can be assessed and appraised along wheel tracks or on turning strips with more effects on top soil (Balbuen et al. 2000). Hetz (2001) suggested that heavy tractors and field machines applied high amount of pressure on soil; however, the magnitude of pressure can be varied according to soil texture. For instance, in coarse-textured soils, axle load exerted pressure in vertical direction; on the other hand, in fine-textured soils, transmission would be in multidirectional soil (Smith et al. 2000). Possible reason for such variation could be due to variation in the proportion of macropores in different textured soils (Smith et al. 2000; Radford et al. 2000; Ridge 2002). The severity of detrimental effects caused by machine size and/or axle load on crop yield can be contingent to the degree of antecedent soil moisture, soil texture, and tillage systems (Salire et al. 1994; Soane and Van Ouwerkerk 1994). Therefore, some of the researchers proposed soil and climate data as an independent variable in exaggerating the susceptibility of soil towards compaction (Batey 2009). However, combined effects of high axle load with high moisture could result in soil compaction to deeper depth (Ansorge and Godwin 2007). Any mechanical energy that impacts individual soil particles can cause compaction. Vibration due to heavy farm mechanical implements can compact soils effectively at higher moisture contents. Vibrations actually impose additional impact and pressure with high intensity than axle load and other factor on soil particles. Speed of tractor together with vibration intensity can cause significant effect on soil compaction. Vibratory effects and saturation of crawler tractors imposed enough pressure on soil to compact it.

Number and size of wheels and tires The number, size, and type of wheels caused soil compaction to variable extent. A tractor with more number of tires exerts less pressure on soil as compared to tractor with single tire on each side of tractor. This difference is due to high ground pressure exerted by single tire per unit area. A strong relation was observed between tire size, number of tires, and depth of compacted soil (Stephen et al. 1985). Moreover, multitire farm implements showed less compaction as compared to single-tire farm machines, as in multitire farm implements width ratio increases with substantial reduction in inflation pressure (Raper et al. 1994; Schäfer-Landefeld et al. 2004). Moreover, different studies showed that dual tires have less impact on subsoil compaction compared to single tire with same axle load (Thurow et al. 1986; Defossez and Richard 2002; Hamza and Anderson 2005). Therefore, from the literature, it is quite apparent that the number and the size of tires have great impact in causing soil compaction.

Soil-tire interaction and number of passing Though the overuse of heavy machinery has already been recognized as the main reason for soil compaction (Vitlox and Loyen 2002), nonetheless soil-tire interaction is another factor that also influences the magnitude of soil compaction. Factors such as soil type, number of tire, size of tires, and axle load contribute towards soil-tire interaction (Defossez and Richard 2002; Hamza and Anderson 2005). Several studies also highlighted further soil surface area as an important trait while studying soil-tire interaction in relation to soil compaction (Raghavan et al. 1979; Vitlox and Loyen 2002; Saffih-Hdadi et al. 2009). Tire stiffness has also a substantial influence on ground; however, inflation pressure played crucial role in governing the magnitude of soil compaction due to tire stiffness (Saffih-Hdadi et al. 2009). Response of inflation pressure on ground contact pressure and beneath ground surface was studied by Jarosław Pytka (2005), who noted that by lowering the inflation pressure, soil-tire interaction can be modified by altering soil-tire interface pressure, tire performance, and rutting effect. Tractor is an integral part of any farming system; an understanding of its involvement in managing soil-tire interaction might be an essential tool for engineers. Soil-tire interaction could also be determined by selecting tire geometry, tire type, lug design, inflation pressure, and dynamic axle load. Moreover, these parameters could help engineers in designing tires to improve their performance under given conditions.

Subsequent passing over same piece of land could lead to severe soil compaction. In a study, Voorhees (1979) evaluated the impact of the number of tractor passes on soil density and indicated that after pass, significant compaction in clay soil occurs up to the depth of 75 mm, while after three passes, soil compaction propagated to depth ranging from 150 to 300 mm. Other studies also found that repeated passes of agricultural machinery over same location increase soil compaction (Chehaibi et al. 2012; Botta et al. 2009). However, Hamza and Anderson (2005) showed that first pass was more effective in inducing soil compaction as compared to second or third pass, as first pass exerted a significant amount of ground pressure on top soil, whereas under several passes, compaction would be severe in horizons close to soil surface (Wiermann et al. 1999). Infiltration capacity and the number of passing of different implements could be used to determine degree of soil compaction. Infiltration capacity of silt soils decreased up to 80% after multiple passes, while reduction in infiltration capacity was evident only up to 35% (Allen and Musick 1992; Allen and Schneider 1992). Bulk density and cone index are other soil parameters which can be used to examine level of soil compaction after tractor passing; nonetheless, a study showed that the use of bulk density as potential soil parameter is not suitable for studying soil compaction after numerous passing (Brussaard and van Faassen 1994). A tractor with 28 tires increased soil bulk density until fifth pass; following this, bulk density started decreasing; however, cone index was found to be a more suitable parameter to understand the role of number of passing in causing soil compaction (Raghavan and McKyes 1978). This could be due to changes in pore space as well as changed fluxes and storage of gases, water, and nutrients (Brussaard and van Faassen 1994).

3. Soil moisture content

Soil moisture content is the most influencing factor that makes soil susceptible to compaction, as penetration resistance increases and soil water potential decreases (Lipiec et al. 2002). In other words, rising soil moisture content causes reduction in macropore spaces and leads to decline in load support capacity of the soil (Kondo and Junior 1999) and permissible ground pressure (Medvedev and Cybulko 1995). Moreover, contribution of soil water content towards soil compaction is dependent on deformability of soil, precompression value, stress dissemination ability, and contact area between soil and tire. Soil gets compacted up to a certain value of soil moisture availability, regarded as optimum soil moisture; above this limit, decrease in soil compaction occurred as soil becomes increasingly plastic and incompressible. It is well documented that the drier the soil, the lower will be stress transformation and the lower will be deformation in soil structure (Batey 2009). It could be a great deal to supervise supportive role of water contents in causing soil compaction, while scheduling farm trafficking and cultivation operations (Ohu et al. 1989). Several studies revealed numerous factors associated with soil degradation, including high moisture content, more number of passes, and timing of tillage (Bakker and Davis 1995; Håkansson and Lipiec 2000). Ground pressure up to 160 kPa exerted on moist soil at a depth of 12–17 cm resulted in significant increase in bulk density with significant decrease in air permeability and macroporosity, while only minor changes were noticed in soil structure at depth of 32–37 and 52–57 cm, when ground pressure of 130 kPa was applied (Gysi et al. 1999). Thus, it can be suggested that in order to minimize compaction, it is important to till soil at appropriate soil water content. Decrease in total porosity is accompanied with increase in soil moisture content, causing compaction to deeper in soil profile (Soane and Van Ouwerkerk 1994; Batey 2009). Depth and width of compacted zone are governed by high moisture content, causing low structural porosity and high structural deformation. It is well documented that decrease in bulk density coupled with increase in soil moisture causes reduction in permissible ground pressure of agricultural vehicles to permit crop production (Medvedev and Cybulko 1995). Soil moisture content also determined aggregate stability and tensile strength of soil aggregates. Study by Lipiec and Tarkiewicz (1986) elicited that increase in soil moisture content caused decrease in aggregate diameter and porosity, while increase in bulk density which is a character of compacted zone leads to increase in aggregate tensile strength. The effect of soil moisture is much stronger in the subsoil than in the topsoil; however, for comparison and calculation of soil moisture content, determination of liquid, plastic, and solid limits of soil might be a better scale (Quiroga et al. 1999). These limits are the functions of clay contents and their mineralogical characteristics.

4. Treading action of animals

Livestock production is an integral part of agriculture worldwide. Continuous and long season grazing has attained substantial importance, while dealing with soil compaction. It has been reported that constant grazing and livestock walking caused considerable effects on soil properties and have negative effects on soil stability index (e.g., Imhof et al. 2000; Silva et al. 2000b) Grazing animals also disrupt soil aggregates, resulting in reduction in soil aggregate stability (Ferrero and Lipiec 2000). Other negative effects associated with animal trading are associated with reduction in soil structure and/or soil porosity (Di et al. 2001). Extent of alteration in soil properties due to the livestock depends on soil type and soil moisture; (e.g.,) fine-textured soils are more vulnerable to trampling action of grazing animals than coarse-textured soil (Batey 2009). Moreover, dry soil faced less trampling action due to high aggregate stability index; however, moist soils are more vulnerable to compaction (Mosaddeghi et al. 2000).

Under intensive agriculture, escalation of dairy farming and livestock rearing exaggerates the deleterious effects of trampling on soil quality, thus results in sizeable reduction in production level and pasture quality (Mitchell and Berry 2001). Animals' hooves exerted ground pressure in same way as applied by tractor tires. In tractor, the weight of axle load has been applied on soil via tires; similarly, the whole weight of animal may apply great pressure on soil under its hooves. Compaction by animals seems to be more destructive than tractor, though tires have more width than animal's hoof, while ground pressure decreases with increase in width. Therefore, more pressure will be exerted on given soil area under hooves. Furthermore, animal weight and soil moisture content determine the depth of soil compaction by trampling. Experiments showed that the effects of trampling in causing soil compaction at different soil depths differed in different soil types. In soil depths of trampling-induced compacted soils, some reported compaction effects were limited to depth of 20 cm (Ferrero and Lipiec 2000; Terashima et al. 1999), some observed highest soil density at the top 5-cm soil layer (Vzzotto et al. 2000), and other suggested dense zone with reduced water infiltration to depth of 7.5 cm (Usman 1994).

Since treading action of animals affected all soil properties, soil penetration resistance is a crucial soil property, which is highly sensitive to animal trampling action. Hamza and Anderson (2005) reported critical values of penetration resistance in response to grazing, water table depth, and weight of animal. They noted that permissible limits of penetration resistance were ranged from 600 to 800 kPa, depending on animal's weight, homogeneity and heterogeneity in soil, and vegetation. The level of grazing also causes soil compaction to a varied extent, (e.g.,) more soil compaction with high bulk density was observed in heavy-grazed soil as compared to light-grazed or medium-grazed soils (Mapfumo et al. 1999). Furthermore, soil saturation, root ratio, and soil water infiltration can also be indictors of examining soil compaction (Vahhabi et al. 2001; Gokbulak 1998; Mwendera and Saleem 1997), as these soil properties are highly vulnerable to trampling action of animals.

5. Soil organic matter

Organic matter in soil plays significant role in maintaining soil biological activities. High organic matter results in higher stability index, high soil quality, and productivity, while lower organic matter contents in soil make soil more susceptible to soil compaction (Wortman and Jasa 2003). The theory behind the preventing action of organic matter might be examined by the presence of residues over soil surface, which is a prominent characteristic of conservation tillage system. These residues might absorb the pressure exerted by high axle load, preventing to create voids in soil. Furthermore, organic matter/residues on soil surface have been shown to cushion the effects of soil compaction (Hamza and Anderson 2005). A significant layer of surface crop residues might be compressed under compressing action of heavy machineries, but they can retain their shape and structure once the traffic has passed. Organic residues may act like a sponge that can be compressed but comes back to its normal shape. However, excessive traffic may break organic residue, might be a result of tire slipping or soil stirring actions of tires. Organic residues in soil profile are more significant than on surface, as this organic matter attached to soil particles especially clay particles and binds microsoil and macrosoil aggregates, thus preventing soil from become compacted by the action of heavy machines. Conclusively, soil organic matter is a very important soil property, which can determine the magnitude of soil compaction. More soil organic matter and less would be a result of susceptibility of soil towards compaction.

7. Raindrop impact

Direct beating action of raindrop can disperse soil particles via breaking the soil surface. Soil surface got cracks, and fine particle becomes separated from soil clods, which when accompanied with water stagnation settle down to make hard layer of soil thus causing soil compaction. Raindrop when fell on ground transfers its energy to soil particles, and when energy becomes higher than energy-carrying/bearing capacity of soil particles, they (particles) became separated from soil. In rain-fed areas, heavy and deep tillage is employed prior to rainfall especially monsoon rainfall in order to infiltrate more water and reduce runoff. After rainfall, land leveling is done using heavy planker to create natural soil mulch for water conservation in soil. The high weight of planker and tractor when coupled with ample moisture in soil can lead to soil compaction. Though rainfall is the only source of water in those areas, the degree of soil compaction is also high. Plankers with less weight or layer of residues on soil surface before rainfall could be appropriate technique to reduce soil compaction and direct tearing action of rainfall. No exact study has been reported; however, it will be more important to study this in humid areas.

Consequences of soil compaction

Literature has elicited numerous factors responsible for soil compaction. Most of the factors are intensively employed in modern agriculture. The importance of these factors especially mechanization cannot be rendered in today's agriculture. However, knowledge regarding the optimum limits of these factors may help in controlling compaction. Furthermore, the detrimental consequences of soil compaction can also be taken under consideration while controlling compaction. Soil compaction caused numerous effects on soil and crop plant. The detrimental effects of soil compaction on soil properties and crop growth and development will be reviewed in this section. A summary of the knowledge regarding the effects on soil compaction on soil properties and crop plant's morphological and physiological growth has been presented in Fig. 2; however, significant explanation has been provided below.

On soil physical properties

1. Total porosity

Soil consists of three types of pores; macropores, mesopores, and micropores. Air-filled pores are macropores, which supply oxygen to soil flora and fauna. Decrease in macropores resulted in the development of anoxia conditions, thus interferes with crop growth and development. Soil compaction reduces pore spaces and consequently checks the transfusion and transportation of air and water within soil profile and also water retention characteristic (Dexter 2004). Alteration in pore size distribution due to compaction resulted in increased runoff, decreased infiltration, and high erosion losses. Heavy use of farm implements enforced high axle load and ground pressure on soil, causing shrinkage in pores, and consequently, volume of pores decreased (Pagliai and Vignozzi 2002). As reviewed in the above sections, tillage system has noticeable effects on pore size distribution. Under conventional tillage system, extensive loosening of soil develops more macropores at the beginning of the season (Botta 2000), while later on, macropores became reduced due to soil compaction. Structural instability of pores is highly dependent to timing, intensity of field traffic, and rainfall pattern and tends to change with alteration in these factors (Mapa et al. 1986; Karunatilake and van Es 2002). Dexter (1988) defined soil compaction as a deteriorating process that alters spatial arrangement, size, and shape pores in soil profile. In another study by Boizard et al. (2013), who examined the effect of repeated wheeling on pore size distribution and pore volume, they further noted that no visible macropores were observed in highly compacted zone. Moreover, massive structure disruption and smooth breaking surface are also developed in this zone. The destruction effect of compact zone has also been reported by Koch et al. (2008), who pointed out that compacted zone negatively affects macropore volume and air permeability of the topsoil (0.05–0.1 and 0.18–0.23 m) and subsoil (0.4–0.45 m) layers.

2. Hydraulic conductivity

Hydraulic conductivity especially saturated is highly sensitive to soil deformation (e.g., Green et al. 2003), especially soil

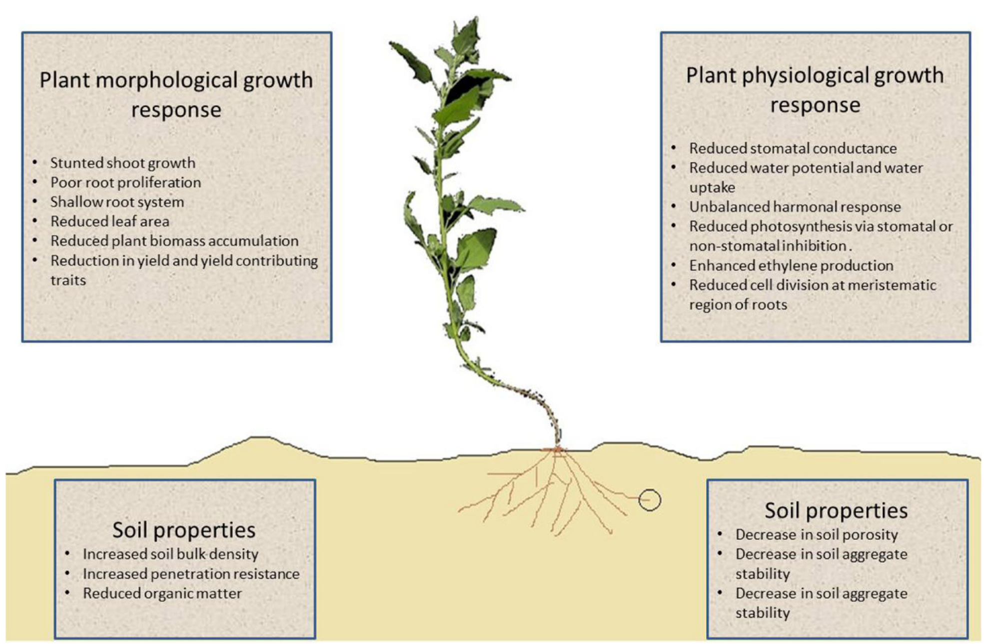

Fig. 2 Summary of the knowledge of the effects of soil compaction on soil plant morphological and physiological growth and soil properties

compaction (e.g., Whalley et al. 1995) and alteration in porosity (e.g., Matthews et al. 2010). Decrease in soil aggregate stability, increase in soil bulk density, and decrease in air voids result in decrease in hydraulic conductivity of soil (Nayak et al. 2007). Moreover, Radford et al. (2000) reported that increase in soil strength due to compaction also reduces hydraulic conductivity. Saturated hydraulic conductivity is a function of structural distribution of pores, more vulnerable to reduction than unsaturated hydraulic conductivity. Under this milieu, image analysis of micropores revealed that saturated hydraulic conductivity is in linear relation with degree of availability of elongated soil pores. The higher the elongated soil pores, the higher will be the conductivity, whereas soil compaction decreases total porosity, consequently decreased soil hydraulic conductivity (Pagliai et al. 2003). Among soil pore type, water is retained in micropores rather than macropores, so even if average porosity is the same, the magnitude of micropores and macropores might be different (Kutílek and Nielsen 1994). Soils having more micropores have high saturated hydraulic conductivity than soils with more macropores.

Type of machinery, tire inflation, and ground pressure exerted varying levels of stress for soil compaction and also governed distribution of compacting force in soil either vertically or horizontally. Thus, examination of effects of vertical soil compaction or horizontal soil compaction on hydraulic conductivity might be conducted possibly and practically (Henshall and Smith 1989). Furthermore, degree of alteration in hydraulic conductivity varies with different soil depths even within the same soil profiles. Saturated hydraulic conductivity, for example, was found lower in top soil than in subsoil at the same bulk density, as noted by Keiko (2005). They also found that varying values of conductivity at top soil were showed scattered when correlated with mean value while of subsoil were very close to bulk density curve. This implies that bulk density is high in subsoil compaction than in top soil; consequently, reduction in hydraulic conductivity occurs in the same fashion. Furthermore, this was further substantiated as Unger and Kaspar (1994) computed effect of single pass and multiple passes on reducing extent of reduction in hydraulic conductivity at different soil depths. They noticed that at deeper depths, significant reduction of saturated hydraulic conductivity would occur; however, these depths varied with number of passing and wheel load.

3. Aggregate stability

Soil aggregate stability is an important index of soil quality, and soil physical property affects soil productivity and sustainability. Soil aggregates are actually groups of soil particles that stick together as result of cohesive forces among particles and interaction of organic matter, cations, and anions with soil particles. Aggregate stability index defines the capability of soil particles to oppose dispersion and degeneration of soil peds/clods. Tillage exerted series of disruptive forces to disintegrate soil particle thus reducing stability index of soil. Soil with high stability index is more productive, produces higher crop yield, while with low stability index, soil erosion looses are high. Soil compaction reduces formation of soil aggregates; it becomes worsen when high axle load and high moisture content together assaulted on soil. Spatial arrangement of these aggregates within soil profile determines the extent of effects of soil compaction (Dexter 1988). Heavy tillage, high axle load, ample moisture, rutting action of tire, and velocity and intensity of wheeling affect the soil aggregate stability. Alteration in aggregate stability is an early indication of degradation or deterioration of soil quality. Among tillage systems, conservation tillage system resulted in high structural regeneration and aggregate formation than conventional tillage system (Alakkuku et al. 2003). Furthermore, some other authors also reported that conventional tillage deteriorates soil quality via reduction in organic matter content, soil aggregates, and porosity, while conservation tillage improves soil quality (Wiermann et al. 2000). In another study by Pagliai and Vignozzi (2002), heavy tillage together with moisture reduces volume of pores, and consequently, soil aggregates pressed together and their structures become disintegrated and altered in non-accommodating shapes (Defossez and Richard 2002). Compacted soils characterized by low pore spaces and low soil aggregate stability index resulted in reduced infiltration and increased runoff. Surface crusting is another indicator of compacted soil, associated with low pore spaces and weak aggregates resulted in high soil erosion losses (Way et al. 2005). Sandy soils have more dispersed particles with less aggregate stability. Soil compaction has relatively more destructive effects on clayey soils as they have more binding of soil aggregates than sandy soils.

4. Penetration resistance

Penetration resistance elicits the work done by root to enter in soil (Braim et al. 1992). Higher mechanical impudence, higher will be compaction, results in higher penetration resistance, which results in more work done by roots. This soil property is widely employed to compute the degree of changes in soil porosity and aggregate stability (Dexter et al. 2004). Soil compaction caused significant increase in penetration resistance (Chaney et al. 1985). Penetration resistance increases with increase in bulk density and lower water potential (Douglas 1992). Root penetrability reduces with increase in penetration resistance (Unger and Kaspar 1994). The decrease in penetration level is directly correlated with increase in water potential. Dry soils have more penetration resistance as reported by Lipiec et al. (2002), who noted that in the presence of high soil water, soil strength and penetration resistance would be low (Horn et al. 1995).

5. Bulk density

Bulk density is defined as oven dry weight of soil per unit volume. Bulk density determines the extent of porosity in soil. Soils with good structure are characterized by increased soil macroaggregates and porosity. Increase in bulk density is reported with increase in soil compaction, as compacting forces squeeze the volume of soil via eliminating pore spaces. External stress (high axle load) reduces aggregate stability of soil, thus increasing build density of soil. It is well documented that increase in bulk density caused reduction in yield as observed in Argentina. Ressia et al. (1998) reported if bulk density >1.2 mg m^{-3} resulted in 30% decrease in maize yield. Other consequences associated with increase in bulk density due to compaction are high penetration resistance, less infiltration, high runoff, and more soil erosion. The number of passing also affects the extent of bulk density; Allen and Musick (1997) reported that bulk density could be increased up to 20% due to multiwheeling. Under different tillage regimes, bulk density varies, as conventional tillage initially resulted in high porosity and less bulk density in early season, while later on, due to compaction-causing agents, the number of pores decreases and bulk density increases, could be prolonged (Yavuzcan et al. 2000). However, under conventional tillage system, initially bulk density and penetration resistance are more, while the action of natural biological agents (e.g., worms, fungi) improves productivity of soil by enhancing aggregate stability, porosity, and organic matter and reducing bulk density.

On crop performance

Morphological alterations Soil compaction reduces crop yield and growth by influencing numerous morphological and physiological processes (Fig. 2). Numerous studies showed different extent of growth and yield reduction in numerous plant species due to soil compaction (Table 1). Growth and development of aboveground crop plant depend on the performance of belowground part (root); however, root performance is majorly governed by soil conditions in root rhizosphere (Trouse 1977). Soil compaction results in the significant reduction in soil porosity and soil aeration (as mentioned above); roots show stunted growth and poor root proliferation (Dexter 2004). Root-soil compaction interaction may be complex, depends on the extent of soil compaction and the degree of modifications in soil properties. Reduction in root growth might be associated with mechanical injury to taproots, high penetration resistance of compacted soil, and less nutrient bioavailability (Rosolem et al. 2002). It is well documented that root penetration restricted to significant level when soil penetration resistance approaches to 2 MPa pressure, and above this limit, no roots virtually were able to grow (Taylor et al. 1966).

Besides interfering root proliferation in soil, soil compaction also causes numerous effects on aboveground parts. Several studies revealed that soil compaction caused substantial yield reduction in many crops (Botta et al. 2002; Jorajuria et al. 1997). Soil compaction reduces plant growth by reduction of the development of plants. A study showed that reduced plant height, stem diameter, and damaged roots were

Table 1 Effects of soil compaction on plant growth and yield

Plant species	Soil compaction depth	Soil compaction induced by	Effects on plant growth and/or yield	Reference
Festuca rubra	0–15 cm	Brinkman roller simulator (BTS)	Reduction in RDM (8.80%), RLD (10.62%), and RSA (6.14%)	Głąb and Szewczyk (2015)
Festuca ovina	0–15 cm	BTS	Significant reduction in RDM (21.36%), RLD (23.14%), and RSA (20.69%)	
Festuca arundinaceae	0–15 cm	BTS	Reduction in RDM (26.50%), RLD (27.17%), and RSA (20.30%)	
Agostis capillaris	0–15 cm	BTS	Reduction in RLD (7.42%)	
Agostis stolonifera	0–15 cm	BTS	Reduction in RDM (17.98%), RLD (27.42%), and RSA (−14.80%)	
Hordium vulgare L.	0–60 cm	Tactor MTZ-82	Reduction in RDM (74%)	Trükmann et al. (2008)
Hordium vulgare L.	0–40 cm	Tractor	Reduction in RDM (39.09%)	Lipiec et al. (2003)
Quercus castaneifolia	–	Compaction hammer	Reduction in RDM (62.84%) and TBM (53.38%)	Jourgholami et al. (2016)
Raphanus sativus	15–50 cm	Wheel trafficking	Reduction in RDM (31%) and TBM (31.25%)	Chen and Weil (2010)
Brassica napus	15–50 cm	Wheel trafficking	Reduction in RDM (50%) and TBM (62.89%)	
Secale cereale	15–50 cm	Wheel trafficking	Reduction in TBM (32.01%)	
Cicer arietinum	1.2–1.6 mg/m^3	–	Reduction in SDW (51%)	Mohanty et al. (2015)
Triticum aestivum Cult. Avalon	0.75 MPa	–	Reduction in TBM (79.35%)	Jin et al. (2015)
Triticum aestivum Cult. Battalion	0.75 MPa	–	Reduction in TBM (70.63%)	
Triticum aestivum Cult. Cadenza	0.75 MPa	–	Reduction in TBM (87.61%)	
Triticum aestivum Cult. Robigus	0.75 MPa	–	Reduction in TBM (77.97%)	
Cork oak	1.37 MPa	–	Reduction in RDM (44.01), MRD (26.17%), PH (36.4%), and TBM (31.27%)	Jourgholami et al. (2016)

RDM root dry matter, *RLD* root length density, *RSA* root surface area, *MRD* mean root diameter, *SDM* shoot dry matter, *PH* plant height, *TBM* total biomass due to reduced nutrient uptake in compacted soils (Ying et al. 2007). Shoot density, verdure, and root growth of turf grasses were reduced twofold due to compaction (Carrow 1980). Ishaq et al. (2001a) reported that 12 to 23% decrease in grain yield and 9 to 20% decrease in straw yield were noted due to subsoil compaction. They also observed that wheat plants undergone with reduced number of shoots per unit area, root growth, and finer and denser root system in upper soil layer of 10 cm. Moreover, in a study, it was noted that for each 100 kg m^{-3} increase in bulk density, maize grain yield reduced by 18% (Canarache et al. 1984). Moreover, Montagu et al. (2001) reported that there was less seed germination and reduced early root growth in compacted zone, might be ascribed to reduced nutrient uptake and poor aeration. Nonetheless, seed germination in compacted soil also depends on clay contents and soil moisture level. For instance, Ishaq et al. (2001b) noted poor seed germination and stunted root growth in compacted soils having high clay contents under dry climate. Reductions in soil water availability due to poor water infiltration and less number of macropores account for reduced root growth and lower N uptake (Rosolem et al. 2002). Several studies have documented increased rates of denitrification or NO production in compacted soils (Torbert and Wood 1992), but other N losses may also occur through increased surface runoff in compacted soils due to lower water infiltration.

Physiological alterations Soil compaction also induces soil-deficit conditions due to lower water holding or infiltration in soil. Such water-deficit conditions on the other hand cause alteration in different physiological processes. Some researchers found that in compacted soils, reduced water uptake resulted in reduced stomatal conductance and higher accumulation of abscisic acid (ABA) in roots (Tardieu et al. 1992). Young et al. (1997) attributed the reduction in leaf appearance rate to a hormonal signal generated by impeded roots. Soil compaction induced a limitation in root growth that can also be reflected by a decrease in the root/shoot ratio. It is now known that a limitation in root sink activity results in the accumulation of carbohydrates in leaves, thus regulating the rate of carbon assimilation (Arp 1991). This root-to-shoot feedback is believed to occur in the form of an increase in ABA concentration in the shoot xylem sap (Tardieu et al. 1992; Turner 1997). Such an increase could raise stomatal resistance, therefore reducing carbon fixation. Moreover, plants exposed to severe soil hardness also result in reduced photosynthesis via stomatal or non-stomatal inhibition. Impeded roots to compaction may face anaerobic condition due to less aeration and high respiration, which can reduce plant growth and development. In maize, the increase in soil bulk density decreased carbon assimilation rate especially in early growth stages, and the main effect of soil compaction on assimilate partitioning occurred on carbon exudation, which increased considerably to the detriment of root carbon (Tubeileh et al. 2003). Further, 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 of triticale and maize (Grzesiak 2009). Furthermore, along with the restriction of root growth, significant decline in ψ, F_v/F_m, and gas exchange in triticale and maize (Grzesiak 2009) was observed. 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 (Grzesiak 2009). The results indicated that damages in photosynthesis, water relation, and shoot growth by soil compaction would be closely related to sensitivity of root system architecture to high mechanical impedance of soil (Tubeileh et al. 2003). A clear relation was proposed by William et al. (1994) that reduction in stomatal conductance, resulted in high xylem sap ABA, resulted in reduction in leaf expansion of soil compaction-stressed plants. However, Munns (1992) argued that increased ethylene production could be correlated to reductions in shoot growth (Morgan et al. 1993). Ethylene may act as a root source chemical signal and may also be involved in mediating shoot responses to soil compaction (He et al. 1996). For instance, Hussain et al. (1999) described the role of ethylene in mediating the impact of soil compaction on shoot and root growth in tomato. Plants when subjected to soil compaction exhibited least physiological growth at merismatic region.

Conclusion

Soil compaction is the worst type of land degradation that limits agricultural productivity. Numerous factors are responsible for soil compaction, comprised of high mechanical load and tillage system, and its associated adversities resulted in alteration in soil health via modifying soil physical and chemical activities. Besides these effects, soil compaction repressed the crop performance by influencing the growth and the development of plant. Stunted growth, leaf discoloration, reduced plant height, and shallow root system are predominant morphological effects of soil compaction, while less nutrient uptake, reduced leaf gas exchange, carbon assimilation, and less translocation of photosynthates are detrimental effects of soil compaction.

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