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Research Article

IMPACT OF SOIL COMPACTION ON SOIL PHYSICAL PROPERTIES AND ROOT GROWTH: A REVIEW

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ABSTRACT
Mechanization of farm operations, intensive agriculture and continuous use of farm machinery has resulted in soil compaction. Soil compaction affects soil physical properties, plant growth, root growth and yield of crops. It increases bulk density and penetration resistance, decreases porosity, infiltration rate and hydraulic conductivity. Vehicular traffic and puddling resulted in formation of compacted subsoil layer in the root zone at 10-40 cm depth that restricts the root growth and root density of plants. The reduction in root growth and density further decreases nutrient uptake and ultimately crop yield. The review of the literature presented shows the need of conservation agriculture to reduce traffic on the soil and subsoiling/chiseling to remove hardpan developed due to traffic and puddling.

Keywords: *Agricultural Machinery, Soil Compaction, Puddling, Soil Physical Properties, Root Growth*

INTRODUCTION
Soil compaction is emerging as a serious problem affecting the yield of field crops leading to soil degradation worldwide. Compaction-induced soil degradation affects about 68 million hectares of land globally (Flowers and Lal, 1998). Soil compaction is the compression of soil by external forces that decrease the volume of pore space while increasing the soil density (Harris 1971). It is a densification and reduction in porosity, associated with changes to the soil structure and an increase in strength and a reduction in hydraulic conductivity (Soane and van Ouwerkerk 1994). A thick compacted layer builds up in the root zone as a consequence of poor tillage practices, primarily as a result of the farmer failing to vary the depth of ploughing over several years (Tursic *et al.*, 2008). The extent of the soil compaction problem is a function of soil type and water content, vehicle weight, speed, ground contact pressure and number of passes, and their interactions with cropping frequency and farming practices (Larson *et al.*, 1994; Chamen *et al.*, 2003). Soil compaction occurs when soil particles are pressed together, reducing pore space between them (DeJong-Hughes, 2001). The existence of high plough sole density layer of 5-15 cm thickness at 10-40 cm soil depth in agricultural soils was reported by Sur and Singh (1972) and particularly in extensively puddled soils with rice cultivation (Sidhu, 1980; Sur *et al.*, 1980; Sharma and De Datta, 1986). Puddling is the process of tilling the soil at high moisture content, causing shear and compression of soil particle (Singh, 1961). It destroys soil aggregates and peds, create plastic mud, and thus eliminates most macropores, which transmit water, remaining macropores are filled by dispersed fine particles (Sharma and De Datta, 1986; Adachi, 1990). Puddling also result in non-linear reduction in water flux through soil (Sharma and Bhagat, 1993).

Formation of Subsoil Compact Layer
The vast majority of soil compaction in modern agriculture is caused by vehicular traffic (Flowers and Lal, 1998). The most common causes are agricultural machines such as tractors, harvesters and various other cultivation implements, as wheels travelling over moist and loose soils (Alakuku *et al.*, 2003). The degree of compaction depends on the soil strength, which is influenced by intrinsic soil properties such as texture and soil organic matter contents (Larson *et al.*, 1980; Hettiaratchi, 1987), structure of the tilled layer at wheeling (Horn *et al.*, 1994) and its water content (Guerif, 1984; Kirby and Kirchhoff, 1990) and loading, which depends on axle load, tyre dimensions and velocity, as well as soil-tyre interaction (Lebert *et al.*, 1998). High axle load traffic (10 Mg axle load, 300 KPa inflation pressure) most often cause detectable differences in soil physical properties to around 50 cm depth on soils with clay content varying

from 2 to 65 per cent (Arvidsson, 2001). Abebe *et al.*, (1989) concluded that the surface and the subsurface soil deformation characteristics, which were taken as indicative values of soil compactibility, strongly indicate that the maximum compaction occurred during the first three passes of a loaded wheel. Under field conditions, soil compaction is greatly influenced by the axle load and the number of tyre passes during farm operations (Canillas and Salokhe, 2001). Raper *et al.*, (1998) in an experiment found that soil that was initially completely disrupted to a depth of 50 cm was re-consolidated by traffic into a soil condition similar to one that had never received a subsoiling treatment. It was also found that traffic decreased the total soil volume estimated for root growth using a 2 MPa limiting cone index value, but not the maximum rooting depth beneath the row, when an annual in-row sub-soiling practice was used. Abu-Hamdeh (2003a) found that the intensity of subsoil compaction occurring as vehicle tyre goes deeper with increasing axle load and tyre inflation pressure. The study showed that increasing tyre inflation pressure and axle load increased dry bulk density and cone penetration resistance. It has been estimated that over 30 per cent of ground area is trafficked by the tyres of heavy machinery even in genuine zero tillage systems (one pass at sowing). While under minimum tillage (2–3 passes) it is likely to exceed 60 per cent and in conventional tillage (multiple passes) it would exceed to 100 per cent ground area is trafficked by the tyres of heavy machinery during one cropping cycle (Tullberg, 1990). Tillage and traffic using heavy machines can also induce subsoil compaction in different soil types and climatic conditions in cropped systems (Raper *et al.*, 1998; Mosaddeghi *et al.*, 2000). Ghildyal and Satyanarayana (1965) reported that the medium textured soils were more prone to compaction than that in light and heavier one. In coarse textured soils, the dominant penetration of stress was in the vertical direction, while in soil with a finer texture stress propagation was multi-directional (Ellies *et al.*, 2000). However, it was observed that in soil with a good structure, compaction due to axle load was not so deep and strong.

Persistence of Subsoil Compact Layer

Voorhees *et al.*, (1986) observed subsoil compaction even after four seasons of freezing-thawing, while Blake (1976) observed such affects even after 10 seasons. Hakansson *et al.*, (1987) and Lowery and Schular (1991) concluded that compaction effect may persist for about 5 years depending upon mechanical composition of soil especially clay content. According to Logsdon *et al.*, (1992), compaction persisted for 7 years in 35-60 cm zone of clay loam soil. However, subsurface compaction may persist for a longer time, and had been measured 3–11 years after heavy loading (Alakukku, 1996). Radford *et al.*, (2007) concluded through experimentation that compaction by heavy wheel traffic (10 Mg axle load) for 5 years adversely effected compaction of a wet Vertisol, that persisted for 5 years due to insufficient wet-dry cycles to swell and shrink the entire compacted layer, a no-tillage regime during the amelioration process, and low earthworm numbers in the compacted soil.

Effect of Soil Compaction on Soil Physical Properties

One soil physical property that is always altered in response to compaction is bulk density of surface and subsurface soil. Most of the workers (Patel and Singh, 1981), Ankeny *et al.*, (1990), Badalıkova and Hruby (2006), Radford *et al.*, (2000)) had reported that compaction increases bulk density by disrupting soil aggregates or by compression of soil aggregates forming restrictive layer and thus decreases soil volume by compressing the soil particles (Chaudhary *et al.*, 1991). da Silva *et al.*, (1997) investigated the effects of tillage, wheel traffic, soil texture and organic matter content on dry bulk density and relative bulk density as an index of compactness. The dry bulk density was strongly affected by tillage, wheel traffic, soil texture and organic matter content. The results reveal that intensity of tillage and wheel traffic increases bulk density while addition of organic matter decreases bulk density of soil. Verbist *et al.*, (2007) reported significantly higher penetration resistances between 20 and 40 cm depth, a significantly higher soil bulk density and a 14 per cent decrease in drainage pore space over the surface or top layer.

Soil strength or penetration resistance (PR) is another property affected by compaction. Bulk density is the function of total porosity of soil but penetration resistance is the interplay of many factors or soil properties such as bulk density, water content, soil texture, soil structure and clay mineralogy, etc. Soil strength is used as a measure of soil compaction because it reflects the resistance offered by soil to root penetration (Hamza and Anderson, 2003). Zhang *et al.*, (2006) investigated the relationships between soil water content and penetration resistance (PR), the comparison of soil compaction induced by small power tractor and the medium power tractor, the effect of tractor weight on compaction, the effect of number of tractor passes and tillage on penetration resistance, and the effect of compaction on crop yields, etc. The small powered tillage system created a more compacted plow layer over the medium powered tillage due to increased passes required with this system. Small four-wheeled tractors showed a significantly higher PR over medium power tractor in the surface soil and subsoil. The penetration resistance was significantly and negatively correlated with soil water content at time of penetration resistance measurement (Zhang *et al.*, 2006). After trafficking in a wheat field, the highest penetration resistance was found in the depth interval of 5 to 14 cm. The results of the study further reported that crop yield decreased with increasing numbers of tractor passes. Similar results were also reported by Balbuena *et al.*, (2000), who found that 10 passes significantly affect soil properties of the surface layer to 50 cm depth than that in the 1-pass and no-traffic control treatments. At high soil moisture content, the difference in soil resistance between compacted soil (with traffic) and un-compacted soil (no traffic) was low and usually less than that the value that limits root growth (>2 MPa). However, as soils get drier, soil compaction in the surface layer becomes discernible (Silva *et al.*, 2000). Reichert *et al.*, (2004) reported that penetration resistance for 6-10 cm layer was greater than that in 2 MPa for no tillage, from 30 days after beans seeding until the end of the beans cycle.

Soil compaction considerably affects the soil permeability. Soil infiltration is directly proportional to the stability of soil structure (Tisdall and Adem, 1986), pore size, volume and structure (Patel and Singh, 1981; Ankeny *et al.*, 1990; Badalıkova and Hruby, 2006). Radford *et al.*, (2000) determined the changes in various soil properties immediately after the application of a known compaction load (10 and 2 Mg load on the front and rear axles, respectively) to a wet vertisol and found that compaction was mostly restricted to the top 20 cm of the soil where it decreases the number of pores per unit area in each of the three pore size ranges at soil surface and upto 10 cm depth. Ankeny *et al.*, (1995) found that wheel traffic reduced ponded water infiltration rates, but the impacts varied with soil type. On a silty clay loam, Ankeny *et al.*, (1990) found that wheel traffic reduced unsaturated water infiltration rates, but the reduction was greater in chisel-ploughed soil than that in no-tilled soil. Abo-Abda and Hussain (1990) reported 13-42 per cent reduction in infiltration of sandy soil due to compaction while, Agrawal (1991) attributed reduction in infiltration and percolation losses of water and nutrients due to reduction in water transmitting pores. Tarawally *et al.*, (2004) measured pore size distribution in a Rhodic Ferralsol in western Cuba to study the effects of three levels of soil compaction on soil moisture retention parameters. The study concluded that highest levels of soil compaction were caused at the soil water states corresponding to the field saturation and field capacity treatments. The negative effects of soil compaction on soil hydro-physical properties, denoted by an increased volume of <0.5μm pores at the detriment of the 50–0.5 and >50 μm pore size fractions, followed the similar trend. Marsili *et al.*, (1998) evaluated the change in physical properties of an arable clay soil following passage of rubber and metal-tracked tractors for ploughing on clay soil in centre-south and insular Italy in lucerne. The decrease in macroporosity was greater in treatments involving the rubber-tracked tractor (from 10.6% to 4.0%) than for the metal tracked tractor (from 10.6% to 7.3%).

Hydraulic conductivity decreased and the lowest values were found after one and four passes of the rubber-tracked tractor (1.5 and 0.08 mm h^{-1}, respectively). Kayombo *et al.*, (1991) showed that an increase in axle load from 4 to 8 Mg reduced water infiltration rates upto 35 per cent. Similarly, on a sandy loam soil, water infiltration decreased linearly with the increase in the number of passes (0, 5, 10, 15, and 20) of a tractor of 5 Mg by weight (Ohu *et al.*, 1993). Due to reduction in infiltration rates, Singh *et al.*, (1980) reported improved water use efficiency in rice under highly permeable soils due to reduction in percolation losses as a result of subsoil compaction. On a silt loam, Blanco-Canqui *et al.*, (2004) reported that wheel traffic reduced saturated hydraulic conductivity by about three times and increased bulk density by 6 per cent, averaged across various tillage systems. Canarache *et al.*, (1984) reported 1-3 per cent (w/w) decrease in water content in 0-20 cm soil layer with 30 tractor wheel passes over zero wheel passes in several soils of Romania. A traffic pan of 1.81 Mg m^{-3} density at a depth of 15-25 cm depth reduced water recharge by 2-3 cm in 180 cm soil profile (Sur *et al.*, 1980). This resulted in surface soil layer remain wet longer at each irrigation in plots with compacted subsoil layer than that in uncompacted subsoil layer.

Ghildyal and Satyanarayana (1965) reported decrease in hydraulic conductivity, non-capillary pores and void ratios of sand, sandy loam, sandy clay loam and clay soils with increase in bulk density due to compaction treatments. It had been reported that hydraulic conductivity was directly related to the macropore space while micropores increased at the expense of macropores on compaction. Hydraulic conductivity underneath permanent tracks in a controlled traffic system spreaded laterally into the subsoil (Kirchhof *et al.*, 2000). Soil compaction increased bulk density and strength of the soil and thus affected the conductivity, permeability and diffusivity of water and air (Greenland 1977). Higher bulk density of subsoil has several fold reduced the saturated hydraulic conductivity and greater penetration resistance at given water content than that in layers above or below this subsoil layer (Sur *et al.*, 1980). It also resulted in decreased profile water storage by 2-3 cm when bulk density of subsoil layer exceeds 1.8 Mg m^{-3} from 1.55 Mg m^{-3} in sandy loam soil. The properties of subsoil layer vary with soil texture, water content, type and amount of clay and organic matter content (Singh 1986). Schwen *et al.*, (2011) in a study to measured water infiltration under different compaction levels to characterize the effects of compaction on the soil's porosity and its associated water-conducting properties. The study further concluded that compaction reduced saturated hydraulic conductivity due to distortion of structural flow paths, connectivity and hydraulic effectiveness of many macropores. Compaction rearranged the pore space, resulting in more water-conducting mesopores. Ishaq *et al.*, (2001) conducted a field experiment at Pakistan during 1997–1998 and 1998–1999 on a sandy clay loam soil to study subsoil compaction effects on soil physical properties and crop yield of sorghum. They observed that penetration resistance increased and total porosity and air filled porosity decreased significantly due to subsoil compaction.

Assouline (2006) modelled the relationship between soil bulk density and the water retention curve and reported that increase in the soil bulk density during compaction may influence many aspects of the soil-plant-water relations. Simulation results showed a decrease in the fraction of larger pores and a resulting decrease in water retention at high capillary heads, as well as an increase in smaller pores and the related increase in water retention at relatively low capillary heads was observed. Quiroga *et al.*, (1999) found resistance to penetration and susceptibility to compaction to be inversely related to organic matter content and therefore higher under continuous cultivation. Hydraulic conductivity was lower in cultivated soils, especially in fine textured soils.

The results showed that in sandy to loam soils, an increase of about 5 g kg^{-1} organic matter was required to achieve a 0.06 Mg m^{-3} decrease in bulk density at the optimum proctor moisture content. The results also indicate that the loss of organic matter in the cultivated soils makes them more susceptible to compaction, which not only has adverse mechanical effects on plants growth, development and yield but also gives rise to a considerable reduction in hydraulic conductivity. Sur *et al.*, (1980) reported that the saturated hydraulic conductivity of compact layer at 15-20 cm depth in rice soil was only half to that of saturated hydraulic conductivity in uncompacted soil. This hard layer formed with in as little as in a period of three years on sandy loam soil (Sharma and De Datta 1986).

Assouline *et al.*, (1997) concluded that soil compaction behavior was not only a function of soil texture, but it was also observed to be affected by pH, CEC, clay particle thickness, and by the presence of organic matter, iron oxides, and free aluminum hydroxides, which determine the nature of the resulting cohesive forces between the soil constituents. The results indicated that damages resulting from compaction, following 30 yr of intensive cultivation, were greater in the Palotina soil over the Cascavel soil. Lipiec and Stepniewski (1995) analyzed that soil compaction resulting from vehicular traffic or tillage systems, affects transformations and uptake of nutrients due to changes in soil hydraulic, aeration, and diffusive properties, as well as by its effect on root growth and configuration. Nutrient uptake was reduced by soil compaction. One of the dominant factors affecting soil compaction levels is soil moisture content; with change in compaction level the soil moisture content changes. Under moderate compaction, an increase in nutrient inflow rate per unit length or surface of the roots alleviates a reduction in total nutrient uptake.

Effect of Soil Compaction on Plant Root Growth

A significant effect of soil compaction on root growth and penetration has been reported by a number of scientists around the world. Voorhees *et al.,* (1976) studied compaction effects on soybean nodulation by controlling tractor wheel traffic within soybean plots. After 3 years of wheel traffic in the same inter-row areas, soil compaction from consistent wheel traffic could alter the vertical and horizontal distribution of nodules. Soil compaction can change the morphology and functioning of plant root systems by a number of mechanisms, not only physical, but also biological and chemical (Taylor and Brar, 1991). The roots of different crop species, as well as of cultivars within species, differ considerably in their ability to penetrate through hard soil layers (Singh and Sainju, 1998). Laboski *et al.,* (1998) in a field experiment found that a compacted soil layer confined roots almost entirely to the top 60 cm of soil because it had high soil strength and bulk density and the compacted layer, in turn, retained more moisture for crop use. Rosolem and Takahashi (1998) reported that sub-surface compaction led to an increase in root growth in the superficial soil layer with a corresponding quadratic decrease in root growth in the compacted layer. There was no effect of subsoil compaction on total root length or surface area, soybean growth or nutrition. Soybean root growth decreased by 10 per cent when the soil penetrometer resistance was 0.52 MPa (bulk density of 1.45 Mg m^{-3}) and by 50 per cent when the soil penetrometer resistances was 1.45 MPa (bulk density of 1.69 Mg m^{-3}). Abu-Hamdeh (2003b) reported that in Okra under no-tillage and moldboard-plowed treatments had higher concentration of roots near the base of plants compared to roots of okra in the chisel-plowed treatment. Chan *et al.,* (2006) studied re-compaction due to tractor wheel traffic in a sodic brown clay (Vertisols) under simulated controlled traffic conditions after removal of a pre-existing subsoil pan by deep tillage. The study showed a significant reduction in canola and wheat root growth in the layer under the wheel tracks. While there was no difference in wheat yield, however canola grain yield on the wheel track was only 34 per cent of that between wheel tracks, thus a potential loss in grain yield of canola observed due to compaction by tractor wheel traffic. Masle and Passioura (1987) reported that the increased mechanical impedance reduced water supply from root systems to shoots. Soil compaction treatments decreased leaf number, leaf area and dry matter of shoots and roots, while increasing shoot-to-root dry matter ratio (Grzesiak, 2009). Root growth of maize was heavily restricted by the soil compaction as damage in photosynthesis; plant-water relation and shoot growth under soil compaction were closely related to sensitivity of root systems architecture to high mechanical impedance of soils. The presence of subsoil compacted layer affect the root amount and their distribution pattern in the soils (Sidhu, 1980; Sur *et al.,* 1980; Sur and Sidhu, 1982). Chaudhary *et al.,* (1985) and Gajri and Prihar (1985) reported lesser plant water stress with deeper rooting depth as result of breakage of subsoil compacted layer with deep tillage. Aggarwal and Prihar (1975) reported that roots exert pressure when these grow and their pressure varied with crop, plant age, soil type and moisture conditions. Therefore, roots could overcome some sort of penetration resistance. Garcia *et al.,* (1988) reported that compaction treatments did not significantly affect total root growth, but higher N fertilization overcomes these effects. Punyawardena and Yapa (1990) found that the increase in the compaction decreased the root growth, K uptake, plant height and grain weight of corn. Reichert *et al.,* (2004) reported that roots concentrated mainly in the 5-15 cm layer for no tillage due to higher penetration resistance and were well distributed down to 25 cm depth for chisel tillage, while no restriction to root growth was observed in conventional tillage. The number of days in which the crop experienced soil water outside the Least Limiting Water Range was 18 days for no-tillage, 19 days for conventional tillage, and 13 days for chisel tillage. Abu-Hamdeh (2003a) reported that the plants in compacted plots had a greater concentration of roots near the base of the plants than that in the plants in the zero-load plots. Plants in the subsoiled plots had fewer roots concentrated near the base of the plant over the plants in the non-subsoiled plots for each load.

Management Options to Reduce Soil Compaction

The following management options could be pursued to minimize soil compaction

- Limit traffic to 20-30% of field area by designating traffic lanes: It could save 70-80% area from traffic induced soil compaction.
- Limit machinery weight: Use of light weighted farm machinery or lower axle load lead to lesser compression of soil.
- Avoid working wet soil and improve field drainage: Never till the soil under wet condition, as under wet conditions soil are more prone to compaction because of reduced soil aggregate stability and lubrication of particles due to higher wetness.
- Include deep-rooted crops in crop rotation: Deep root crops should be included in cropping system, it could help in naturally alleviate the negative effects of compacted layer formed due to compaction.
- Vary the depth of tillage or chiseling the soil: It could help in breaking the developed compacted layer.
- Addition of organic matter: It improves aggregates stability and soil structure, thus protect the soil against soil compaction.

Conclusion

Soil compaction increases bulk density and penetration resistance, decreases porosity, infiltration rate and hydraulic conductivity.

The formation of compact layer at any depth resists the penetration of roots, its growth and development and also strongly affects soil-plant-water relations. The conservation agriculture should be practiced to reduce traffic on the soil and subsoiling/chiseling to remove hardpan developed due to traffic and puddling.

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