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REVIEW

A Review on the Effect of Soil Compaction and its Management for Sustainable Crop Production

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Abstract

Purpose Sustainable crop production could contribute to feed and fuel for the ever-increasing global population. The use of heavy agricultural machinery has improved the efficiency of farming operations and increased global food production since the 1950s. But their negative impact on soil includes changing soil structure resulting in deteriorating soil productivity and environmental quality is being noticed for several decades. The purpose of this review is to summarize and help to better understand the effect of heavy machinery, tire inflation pressure, and field traffic on soil properties and crop development, yield, and economics of different farming systems published in the last 20 years.

Methods Search engines such as Google Scholar, Scopus, Science Direct, Springer Link, Wiley Online, Taylor & Francis Online, Academia, and Research Gate platforms were used to collect and review the articles. This review includes indexed journals, conference and symposium proceedings, reports, academic presentations, and thesis/dissertations.

Results Soil compaction increases bulk density and soil strength and reduces soil porosity and soil hydraulic properties. Stunted plant root growth due to compaction of soil affects crop growth and development, and yield. Soil compaction resulting from heavy machinery traffic caused a significant crop yield reduction of as much as 50% or even more, depending upon the magnitude and the severity of compaction of the soil.

Conclusions High gross weight vehicles/machinery traffic damages soil structure and soil environment that are critical for sustainable crop production. The use of heavy machinery such as subsoiling for removing soil compaction results in more fuel use, increased use of energy, cost, and sometimes risks of re-compaction, further deteriorating soil conditions and causing additional adverse environmental consequences. The economics of different farming systems affected by soil compaction, potential soil compaction management strategies, and future research needs have also been discussed.

Keywords Field traffic · Heavy machinery · Soil compaction · Soil management · Sustainable agricultural production · Tire inflation pressure

Nomenclature

BD	Bulk density
CTF	Controlled traffic farming
EC	Electrical conductivity
LTP	Low tire inflation pressure
LWP	Leaf water potential
NDVI	Normalized difference vegetation index
PG	Plant growth
PR	Penetrometer resistance
RG	Root growth
RTF	Random traffic farming
Soil MC	Soil moisture content
Soil OM	Soil organic matter
STP	Standard/high tire inflation pressure
SQIs	Soil quality indicators
X-ray CT	X-ray computed tomography

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Introduction

The rapidly increasing global population is expected to reach 9.6 billion by 2050, which requires increased food production to meet the demand without overwhelming the available resources. Sustainable agricultural production, ensuring food and nutrition security, and minimizing environmental damage are significant challenges that the world is currently facing. The introduction and use of farm machinery have revolutionized modern agricultural production and contributed to increased productivity and sustainability. Despite the benefit of saving money, labor, and timeliness of operation (ECIFM, 2017), heavy farm machinery causes soil compaction that impacts soil structure and decreases crop root growth, overall crop growth and development, and yield (Horn & Fleige, 2003; Chan et al., 2006; McKenzie, 2010). Farm machinery requires varying load demands to perform multiple field operations such as tillage, planting, spraying, and harvesting (Pitla et al., 2016). The increased gross weight of agricultural machinery contributes to the increase in wheel loads and enhances the risk of soil compaction (Chamen, 2015; Keller et al., 2019). The increase in the gross weight of the equipment and an increase in the number of passes play significant roles in enhancing soil compaction in many parts of the world (Horn et al., 2019; Keller et al., 2019). Several studies have shown that soil compaction affects (a) soil properties such as (i) changes soil structure, (ii) increases bulk density (BD), (iii) increases penetrometer resistance (PR), (iv) reduces soil aeration, (v) decreases water infiltration, and (vi) reduces hydraulic conductivity and (b) crop growth by (i) increasing mechanical impediment to root growth, (ii) hampering root architecture, and (iii) decreasing distribution and development of roots (Gan-mor & Clark, 2001; Li et al., 2001; Hamza & Anderson, 2005; Raper & Kirby, 2006; Chan et al., 2006; Radford et al., 2007; Hula et al., 2009; Horn et al., 2019; Keller et al., 2019). A typical example of soil structural damage due to wheel traffic in the agricultural field is shown in Fig. 1. Besides the changes in soil structure, compaction reduces soil pore space and increases soil strength while decreasing root growth and root elongation rate, which results in reduced water and nutrient uptake by crops (Nawaz et al., 2013; Sadras et al., 2016; Colombi & Keller, 2019). The adverse effects of compaction on soil conditions further result in a decrease in plant emergence, plant establishment, and plant height (Sidhu & Duiker, 2006; Millington et al., 2016; Shaheb, 2020). In severe cases, soil compaction substantially impacts crop growth, development, yield, and farm income (Hakansson, 2005; Chan et al., 2006; Botta et al., 2010; Chamen, 2011; Godwin et al., 2017; Shaheb et al., 2018; Colombi & Keller, 2019). Soil compaction at 150 mm depth caused primarily by heavy machinery increased soil BD (1.93 Mg m^{-3}) and led to up to 38% yield loss in wheat (Ishaq et al., 2001a). The effects of compaction can significantly reduce crops yield by 10 to 15% (Godwin et al., 2019). The reduction in yield of corn due to compaction was reported to be as much as 50% (Raghavan et al., 1979), 15 to 43% with 11-Mg axle load followed by tillage (Voorhees, 2000), and 17% by the tillage two-wheel passes of 8-Mg axle load and 300-kPa tire inflation pressure (Abu-Hamdeh, 2010).

Fig. 1 Effect of soil compaction due to machinery traffic showing soil damage, increased waterlogging, and reduced water infiltration. Source: Al-Kaisi et al. (2018)

Agricultural tires and tire inflation pressures have an impact on soil compaction. In general, topsoil compaction is caused by the ground contact pressure of a wheeled machine, while axle load is associated with the compaction in subsoil (Duiker, 2004a; Botta et al., 2008). Application of mechanical loads onto the soil via equipment fitted with pneumatic tires is the primary cause of compaction that damages the soil-water-air-plant systems (Misiewicz, 2010). Shaheb (2020) conducted a 3-year compaction study in Drummer silty clay loam soil in Champaign county, Illinois. The study evaluated high flexion tires fitted on the tillage tractor (10.3 Mg), planting tractor (8.63 Mg), and combine harvester (18.1 Mg) and operated at standard/high (0.14-, 0.12-, and 0.21 MPa) and low tire inflation pressures modes (0.07-, 0.05-, and 0.14 MPa, respectively). The results showed that standard/high inflation pressure tires (STP) caused a significant reduction in yield by 4.13% and 2.62% for corn in the second and third year, respectively, and 3.53% for soybean in the third year in comparison with the low inflation pressure tire system (LTP) (Shaheb, 2020). A brief overview of the effect of soil compaction due to heavy machinery, ground pressure, and field trafficking on soil and crop is presented in Fig. 2.

Strategies for reducing or alleviating soil compaction are focused mainly on subsoiling, control traffic farming (Antille et al., 2015; Chamen, 2015), suitable mechanization

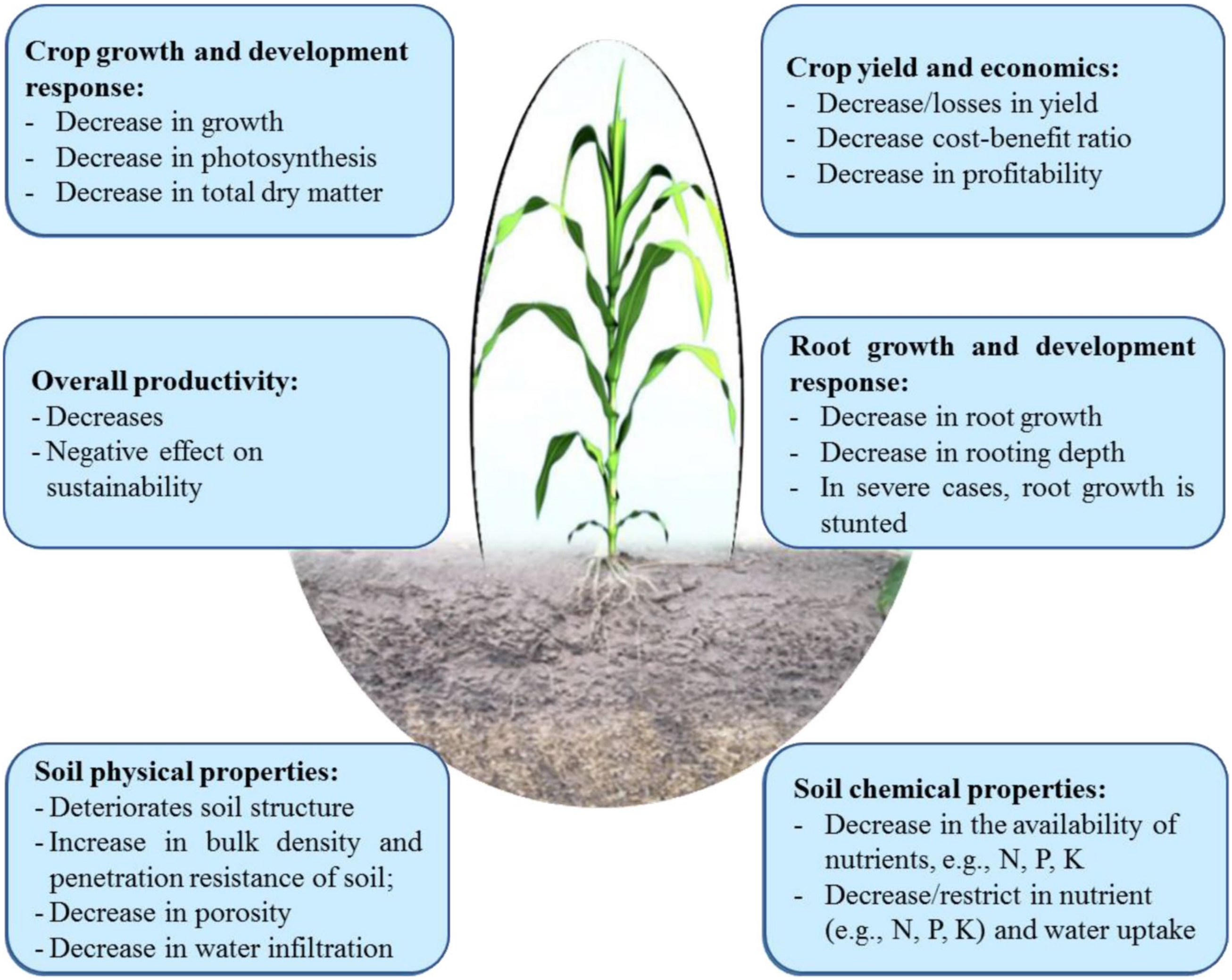

Fig. 2 A summary of the effect of soil compaction on soil properties and agricultural productivity (e.g., corn plant). Adapted from Shaheb et al. (2020)

practices (Godwin et al., 2015), low tire inflation pressure (Van Den Akker et al., 2003; Trautner & Arvidsson, 2003; Smith et al., 2014a, 2014b; Godwin et al., 2017; Shaheb et al., 2018, 2020), conservation tillage (Raper & Kirby, 2006), and incorporation of deep-rooted crops in rotation (Ishaq et al., 2001a, 2001b). Published modeling studies also help to understand, explain, and predict soil compaction (Defossez & Richard, 2002; Schjønning et al., 2008; Berisso et al., 2013; Nawaz et al., 2013). However, there are scopes to emphasize soil compaction modeling works more on machine-soil-plant systems incorporating weather parameters. Subsoiling is often considered effective in removing soil compaction, but this operation sometimes causes a risk of re-compaction of soil (Ishaq et al., 2001a; Schwab et al., 2002; Busscher & Bauer, 2003; Sidhu & Duiker, 2006; Radford et al., 2007; Abu-Hamdeh, 2010; Botta et al., 2010). Nonetheless, deep subsoiling/tillage requires higher energy and fuel for soil treatment. So, the net on-farm cost of different soil compaction mitigation options is negative. Thus, avoiding soil compaction to be more cost-effective than alleviating, particularly true for subsoil compaction (Hallett et al., 2012). However, there is a need to summarize the published studies on the impact of soil compaction on agricultural productivity. The current review will provide detailed information on soil compaction and help better understand the effect of heavy machinery, tire pressure, and field trafficking on soil, crop growth and development, yield, and farm income based on the published literature from the last 20 years. This review (i) summarizes cause and effect of soil compaction on soil properties and crop development in different agroecosystems of the world; (ii) describes in detail how soil properties of diverse ecosystems change due to compaction; (iii) describes the impact of soil compaction in changing soil structure, pore space, water infiltration, soil hydraulic properties, soil air permeability, run-off, and soil erosion; (iv) delineates the possible management strategies of soil compaction; and, finally, (v) outlines future research required to address soil compaction for sustainable soil management and agricultural production.

Methods

The present review used 350 published articles from the last 20 years. The most relevant publications were collected using search engines such as Google Scholar, Scopus, Science Direct, Springer Link, Wiley Online, Taylor & Francis Online, Academia, and Research Gate platforms. It includes indexed journals, conference and symposium proceedings, reports, academic presentations, and thesis/ dissertations. The focus here was to address compaction and related issues as a result of using heavy machinery, ground and tire pressures, and field traffic on soil conditions and its effect on agricultural production. Out of 350 articles, 193 articles were found more relevant to address these issues mentioned before and organized accordingly. Furthermore, efforts have been made to present currently available and possible strategies for alleviating soil compaction to effectively improve soil environment and ecosystems effectively and thus agricultural productivity and sustainability. A summary of the topics, search, and selection procedure used for the review is shown in Fig. 3.

Soil Compaction

Soil compaction reduces the volume of a given mass of soil, i.e., decrease in void ratio and porosity which results in an increases in BD of soil (Keller, 2004). It occurs when soils are subject to stresses that exceed their strength (Soehne, 1958). Stress in soils at the soil-tire interface is a function of tire inflation pressure, equipment load (wheel), tire properties, and soil conditions (Arvidsson & Keller, 2007). The available report shows that approximately 68 million ha of land worldwide have issues due to soil compaction (Oldeman, 1992; Fig. 4), which could increase in the coming years. This implies that there is an urgent need to assess and determine the worldwide affected areas due to compaction,

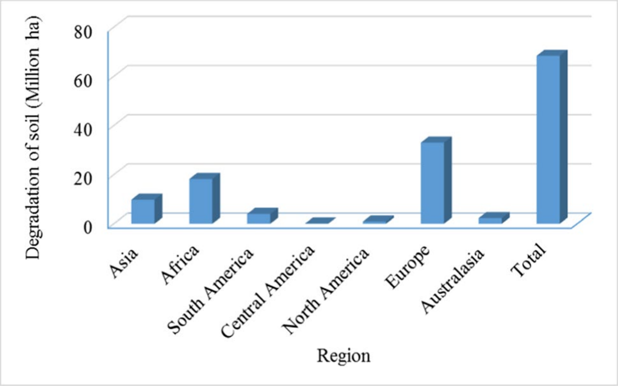

Fig. 4 Degradation of soil due to soil compaction in different continents. Adapted from Oldeman (1992)

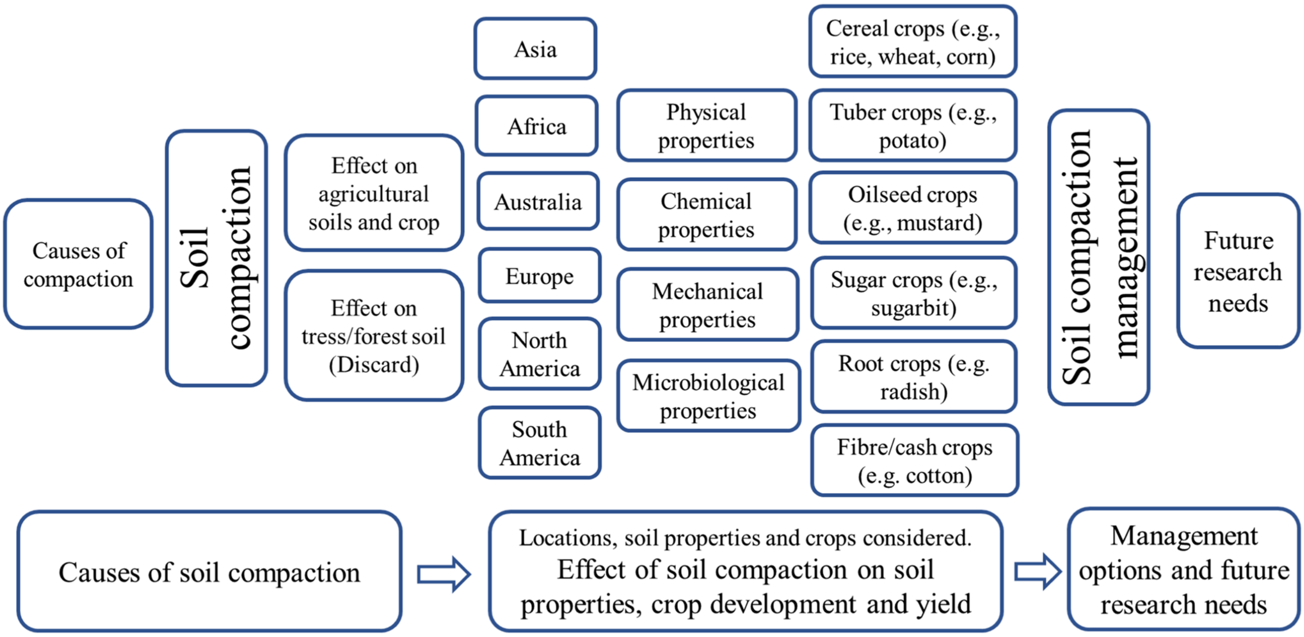

Fig. 3 Flow diagram of the search and selection procedure of the topics considered for the review

especially in regard to commercial agricultural lands. The European Union (Jones et al., 2003) recognized soil compaction as a severe form of soil degradation. The severity of compaction is associated with land use and heavy machinery, indicating that it is the most ubiquitous kind of soil degradation in Central and Eastern Europe (Van den Akker & Soane, 2004).

Compaction is defined as the densification and distortion of soil by which total and air-filled porosity are reduced (Gregory et al., 2015). The Soil Science Society of America (SSSA) defines compaction as "the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density (SSSA, 2008)." It alters the spatial arrangement, size, and shape of soil clods and eventually reduces pore space both inside and outside of clods and soil aggregates (Defossez & Richard, 2002).

There are two types of compaction, viz., topsoil and subsoil compaction. Both are equally significant in the study of soil compaction and management. Kirby (2007) reported that topsoil compaction is associated with stresses imposed by the tire, track, or animal hoof on the soil surface, while subsoil compaction is related to the excessive stresses induced by vehicle load. Lamandé and Schjønning (2010), while assessing soil compaction, reported that stresses applied on the surface of the soil are influenced by tire inflation pressure (evaluated pressure for two tire widths of 560 and 800 mm) and at 900 mm soil depth by vehicle wheel load (30 and 60 kN). Subsoil compaction is recognized as highly persistent (Berisso et al., 2012; Schjønning et al., 2013) and leads to the deterioration of soil physical properties. As a result, subsoil compaction has an impact on functions and ecological services. These undesirable changes in soil structure further exacerbated the impact on crop growth and development, yield, and soil productivity (Lamandé & Schjønning, 2018).

Causes of Soil Compaction

Soil compaction can occur due to both natural and anthropogenic practices (Kirby, 2007). Dense soil layer, soil properties inherited from rock and minerals, presence of higher clay content, environment (wet and dry years) and climate, shrinkage of soil due to drying, trampling by draft, and animal grazing are some of the natural causes of compaction (Van den Akker, 2006; Kirby, 2007; Houšková & Montanarella, 2008; McKenzie, 2010). Wheels and tracks of machinery and soil-engaging tools (Canillas & Salokhe, 2002), heavy machinery, intensive cropping, adopting non-judicious soil management practices, and working with wet soil are examples of anthropogenic or human-induced causes of soil compaction (Hamza & Anderson, 2005; Keller et al., 2019).

Soils with good structures have a greater water holding capacity compared to soils where the structure is damaged. High soil strength influences water and gaseous transport, water flow, soil biological activity, and mechanical strength, which can be altered due to soil compaction (Berisso et al., 2013; Chen et al., 2014). However, deep plowing resulted in a loose soil layer which showed a higher soil water holding capacity than the reduced soil tillage (Kroulík et al., 2007). Soil compaction reduces pore volume and changes pore size and distribution, connectivity, and tortuosity, decreasing gaseous and fluid transport capability and water holding capacity in the soil (Zhang et al., 2007). Repeated wheeling or higher soil stress due to wheel traffic results in deterioration of soil structure by increasing rearrangement of soil aggregates or particles (Horn et al., 2003). This resulted in lower hydraulic conductivity and higher BD at depths of 0–350 mm (Horn et al., 2003) and 0–75 mm, respectively (Blanco-Canqui et al., 2010).

Factors Affecting Soil Compaction

Soil compaction varies across most fields. The key factors affecting soil compaction include soil texture; soil moisture/wetness; soil strength; type and weight of agricultural equipment, tillage layer, tire type, and inflation pressure; and the number of traffic passes (Salokhe & Ninh, 1993; Eliasson, 2005; Hamza & Anderson, 2005; Sakai et al., 2008; Han et al., 2009; Gerasimov & Katarov, 2010). Multiple passes in the field with a heavy tractor (wheel loads 8 Mg) increase the risk of severe soil structural damage deep into the subsoil (Pulido-Moncada et al., 2019). Subsoil structures with coarse, medium, and medium fine-textured soils are weak and more susceptible to compaction (Spoor et al., 2003).

Both weather and climate also influence soil compaction. Soil structural deformation due to field trafficking increases with soil MC and the number of vehicle passes (Hakansson & Lipiec, 2000). Equipment wheel load, tire contact area (machine type), soil wetness during field operations, and the number of passes of wheels (cumulative stresses) significantly influence the extent of soil compaction (Alakukku et al., 2003). Response of soil to high axle loads may vary across soil type and fields. However, some influencing factors such as soil MC, traffic events, equipment-tire configurations, tire inflation pressures, and weather events can exacerbate the response of the soil and degree of compaction (Shaheb et al., 2021). Soil compaction in wet years reduced crop growth and yield. But during the dry years, soil compaction was reported to have a positive influence on crop yield compared to non-compacted soils (Raper, 2005). Moist soils have a lower ability to resist vehicular compaction (Chamen et al., 2015). It is because the degree and magnitude of soil compaction depend on soil strength, which is related to the mechanical strength of soil (determined by soil texture and soil organic matter (OM) content), tillage layer, and wetness of soil (Hamza & Anderson, 2005). The effect of compaction becomes severe under higher soil moisture deficits, which restrict rooting depth; in contrast, when moisture deficit is low, it may have a negligible impact at the same degree of soil compaction (Batey, 2009).

Measurement of Soil Compaction

Dry BD, PR, and total porosity of soils are frequently used to measure the degree of compaction. Koolen and Kuipers (1983) reported that the degree of soil compaction could be expressed by pore space, void ratio, dry volume weight, and bulk weight volume. However, the two key parameters, soil BD and PR, are often used to determine and describe the levels of soil compaction throughout the soil profile (Soane et al., 1987; Duiker, 2002; Hatley et al., 2005; Raper, 2005). Soil cone penetrometer device with a 30° circular cone (ASABE S313.3) is used to characterize the PR of soils and standard protocol (ASABE Standards, 2013, 2018) for data recording and analysis has been followed in most of the published articles on soil compaction. However, it is important to address soil properties and management data when soil PR is presented to describe and better understand the effect of compaction. The most common data are soil type/texture (% clay), OM, soil moisture content (MC), BD by soil layer, cropping/tillage history, soil moisture retention curve, drainage condition, plasticity limit, and size of soil structural units (clods) (ASABE Standards, 2013). The critical values of soil PR that can restrict crop root growth are considered to be between 1.50 and 3.00 MPa (Hakansson, 2005); albeit the value is not constant, the lower threshold value was also reported to be 1.38 MPa (Kulkarni et al., 2010). It is because the level of resistance is influenced by several variables such as soil structure, soil texture, moisture, clay content, and SOM (Reichert et al., 2009). Nutrient uptake of wheat and sorghum decreased due to subsoil compaction in sandy clay loam soil with an increase in soil BD (+17%) from 1.65 to 1.93 Mg m^{-3} and PR from 1.00 to 4.83 MPa (Ishaq et al., 2001a, 2001b). Cone index values >2 MPa have been shown to restrict varying magnitudes of crop root growth, development, and yield (Aase et al., 2001; Hamza & Anderson, 2005). Soil PR is negatively correlated with crop yield. For example, soybean yield decreased with an increase in the PR of soil (Sivarajan et al., 2018). Air-filled porosity of 10% (*v*/v) limits soil aeration and soil PR of 3 MPa is often considered critical to the root growth and development of crops (Hakansson & Lipiec, 2000; Lipiec & Hatano, 2003).

Visual assessment of soils is every so often used to explain soil compaction. Evaluation of soil profiles by conducting soil survey, visual assessment of porosity and soil strength, examination of the plant root system, and semi-quantitative visual and tactile methods can help to describe soil compaction (Spoor et al., 2003; Hatley et al., 2005; Batey, 2009; Munkholm et al., 2013; Obour et al., 2017). Rickson et al. (2012) described seven soil quality indicators (SQIs) that could be used to monitor and measure changes in soil condition or quality in agricultural soils due to compaction. These seven SQIs are soil depth, surface sealing, visual soil evaluation, packing density (e.g., data on bulk density and clay content), aggregate stability, soil water retention properties, and soil erosion rate.

Remote sensing technology has been used to determine and understand soil compaction in temporal and spatial scales. The effect of compaction on silty loam soil was investigated by analyzing plant reflectance response (Kulkarni et al., 2010). The results showed that there was a significant correlation between green normalized difference vegetation index (GNDVI) and soil compaction (e.g., PR of hardpan). Klopfenstein (2016) used remote sensing imagery to determine soil compaction and reported that the predicted model for yield estimation was consistent for wheel trafficked (undercarriage) compaction, suggesting that the remote sensing could be used to assess soil compaction. A recent study (Khanal et al., 2020) reported the possibility of using remote sensing tools for measuring the impact of soil compaction on soil and crop.

X-ray computed tomography (X-ray CT) has been used as a potential tool to investigate the effect of soil compaction and possible modifications in soil structure and other physical properties of soil (Rachman et al., 2005; Mooney, 2006). It is a very useful technique to quantify soil structure, pore characteristics, BD and water content, pore size and pore size distribution, and orientation, which can help to improve the overall understanding of hydrodynamic behavior of soils (Taina et al., 2008; Rab et al., 2014; Beckers et al., 2014; Pires et al., 2020). X-ray CT was used to show visual differences in the soil structure of undisturbed soil cores and quantification of pore characteristics of compacted and uncompacted soils under different tire inflation pressures and tillage systems in sandy loam and silty clay loam soils in the UK and the USA, respectively (Millington et al., 2016; Shaheb et al., 2020).

Benefits of Soil Compaction

Most of the published literature indicates that compaction changes soil structure, which adversely impacts crop growth and development. Nevertheless, some positive effect of soil compaction has also been reported. Soil compaction increased root and shoot mass of oilseed rape and narrow-leafed lupine (Trükmann et al., 2008). The incidence of soil degradation and compaction is reported in some agricultural soils in Scotland (Towers et al., 2006). But, there is no evidence of a serious threat to soil quality in those soils. Instead, the circumstances are recognized to be localized and could be readily remedied (Towers et al., 2006). However, depending on soil types, a small degree of topsoil compaction is beneficial for crop root anchorage and growth (Bouwman & Arts, 2000; Hamza & Anderson, 2005). Moderate compaction facilitated better seed contact with soil particles, which increased corn emergence compared to un-trafficked crop rows, but no significant differences were reported on the yield of corn and the growth and yield of soybean (Sivarajan et al., 2018).

Effect of Soil Compaction on Soil Properties

Equipment size and multiple passes of heavy machinery can deform the soil and increases the degree of compaction. Compaction reduces soil productivity and deteriorates soil functions through increased water runoff and soil erosion (Dejong-hughes et al., 2001; Huber et al., 2008). Several other published reports have indicated that soil compaction due to field traffic reduces soil porosity, hydraulic conductivity, and water infiltration rate while increasing soil strength and soil BD (Raper & Kirby, 2006; Radford et al., 2007; Blanco-Canqui et al., 2010; Hamza et al., 2011; Ji et al., 2013). PR and BD of soils increase with the increase in soil compaction, resulting in a decrease in soil air permeability in wheel tracks and trafficked crop rows compared with no tracks and un-trafficked crop rows (Kaspar et al., 2001; Sweeney et al., 2006; Shaheb, 2020).

Field traffic intensity and high ground pressure have an impact on soil physical properties. Increased axle load (from 1 to 3 kN) and tractor passes cause a significant increase in compaction (Salokhe & Ninh, 1993). The report also highlighted that the maximum compaction of soil took place after the first pass of the tire-wheel, and in later passes, it decreased exponentially. The first tire pass in the soil increased the BD and PR of soil an average of 7 and 6%, respectively, compared to zero passes (Canillas & Salokhe, 2002). It has been estimated that the first traffic pass may cause up to 90% of compaction damages in soil (Badalıkova, 2010). The effect of multiple passes of tractors on the PR of soil is shown in Fig. 5.

A 4-year compaction study conducted in Denmark on a sandy loam soil showed that wheel loads (8 Mg) with 4–5 multiple passes significantly increased soil BD and also changed subsoil structural quality, air permeability, air-filled pore space, gas diffusivity, and pore volume to >50 cm soil depth as compared to multiple passes with 3 Mg wheel loads and zero compaction treatments (Pulido-Moncada et al., 2019). Wheel traffic can cause more negative impacts on soil conditions than intensive cropping systems. Wheel traffic resulted in an increase in soil BD by 19% (from 1.16 to 1.38 Mg m^{-3}), PR by 74% (from 1.78 to 3.10 MPa), shear strength by 165% (from 23 to 61 kPa), and aggregate tensile strength by 153% (from 377 to 955 kPa) over zero-trafficked soils at depths 0–75 mm (Blanco-Canqui et al., 2010). Conventional tillage caused a high number of tire passes on soil, and > 86% of the total area was reported to be trafficked during one cropping season (Kroulík et al., 2011). The total runover areas for two and three repeated traffic events for the conventional tillage systems were 31 and 15.6%, respectively (Kroulík et al., 2011). In general, the repeated traffic resulted in significant damage to soil structure and caused deterioration of soil properties (Hula et al., 2009; Kroulík et al., 2009; Pulido-Moncada et al., 2019). A recent soil compaction study was conducted by Shaheb et al. (2020) in a typical corn and soybean rotation in Illinois. The results showed that the field operations performed by tillage tractor

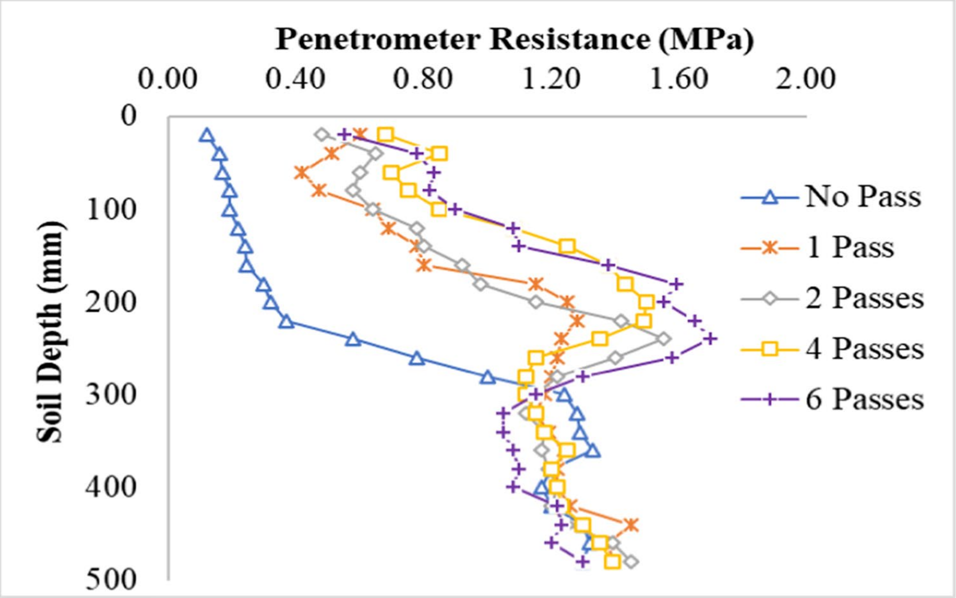

Fig. 5 Effect of soil compaction due to combine harvester traffic (14.5 Mg) on penetrometer resistance of plowed silty loam soil, Wisconsin. Adapted from Wolkoski and Lowery (2008)

(JD7930, 10.3 Mg), planter tractor (JD7700, 8.63 Mg), and a combine harvester (JD9410, 18.14 Mg) caused approximately 75.2, 57.6, and 57.5% of the area to become trafficked for deep tillage, shallow tillage, and no-till systems, respectively (Fig. 6).

The total porosity as a measure of soil compaction was lower for the high inflation pressure tire system (0.17 MPa) compared to the track and low tire pressure systems (0.04 MPa) on a silty clay loam soil in Illinois (Hoeft et al., 2000; Duiker, 2004b). Under low inflation pressure tires, soils had a 17.9% greater number of macropores than that of the standard inflation pressure tires in Drummer silty clay loam soils in Central Illinois (Shaheb et al., 2020). Increased field operations using heavy machinery damaged soil structure which is exacerbated when operating in wet soil with high ground pressure (Botta et al., 2010). Low tire inflation pressure systems reduce the topsoil stresses at a depth of 10 mm, while increased axle load increases subsoil stresses (Arvidsson & Keller, 2007). The benefit of using tires with lower inflation pressures (0.19 to 0.22 MPa) in reducing soil PR (0 to 700 mm depths) was significant as compared to tires with higher inflation pressure (0.25 MPa) (Antille et al., 2013). A multi-year study on fine clay soil showed that topsoil structural damage resulted from high ground pressure tires while large axle loads tend to cause the most significant compaction in subsoils (Botta et al., 2010). The ground pressure of 200–250 kPa also reduced soil water infiltration in compacted soils by more than 80% compared to un-compacted soil (Chyba et al., 2014). However, depending upon the severity, soil compaction can drastically reduce water infiltration rates, increasing the run-off problems, diffuse pollution, and flooding (Godwin et al., 2019).

Effect of Soil Compaction on Agricultural Productivity

Studies were conducted during the early 1940s and 1950s to understand the effect of compaction. These results showed that plant growth and development substantially reduced or restricted under severe compaction (Schafer et al., 1992). Reduced crop growth, decreased stomatal conductance and functions and photosynthesis and enhancement in membrane injury are the first responses by environmentally stressed plants (Ripley et al., 2007). Soil compaction leads to a reduction in crop growth and yield because it restricts crop root systems from penetrating through the compacted soil and extracting soil-bound water (Hula et al., 2009). The wheel track/machinery traffic-induced soil compaction in a soybean crop field is shown in Fig. 7.

Effect of Soil Compaction on Crop Growth and Development

Plant Establishment

Soil compaction reduces crop establishment by increasing soil strength. Plant emergence of corn (Tolon-Becerra et al., 2011; Shaheb, 2020) and barley (Millington et al., 2016) was impaired due to compaction, but the partial effect on plant emergence of soybean (one out of three years) was also reported (Shaheb et al., 2018). Compaction induced by high tire inflation pressure (700 kPa) decreased plant population in no-till soybean and corn production (Sidhu & Duiker, 2006). Lower plant establishment and root dry mass of winter barley in compacted areas were associated with anaerobic conditions as a result of the reduced size of soil

Fig. 6 Estimated area of field trafficking for three typical tillage systems (assumed 33.3% split between tillage systems) experiment in Champaign County, Illinois (Shaheb, 2020)

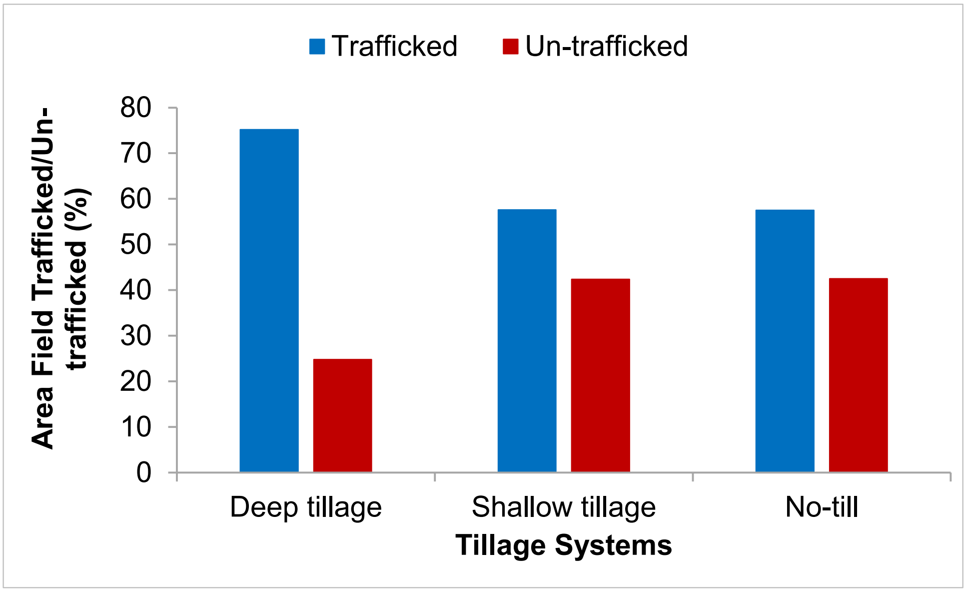

Fig. 7 Soil compaction due to machinery traffic in a soybean crop field. Source: Gruber (2021)

pores (Millington et al., 2016). Furthermore, several other studies reported that soil treatments with subsoiling/deep tillage for alleviating compaction had an adverse effect on subsequent crops' germination (Ishaq et al., 2001a, 2001b; Defossez & Richard, 2002; Gelder et al., 2007).

Plant Height

The effect of soil compaction on plant height was noticeable. Crops suffer more during the early stages of their growth due to soil compaction (Abu-Hamdeh, 2010; Millington et al., 2016). Plant height of corn significantly reduced by 21%, 42 days after planting, and 11% at harvest due to annual road tire compaction compared to control (Sidhu & Duiker, 2006). Compared with the zero load treatment, corn plant height for the 8- and 19-Mg loads treatments was decreased by 5 and 10% in the first year and 5 and 6% in the second year, respectively (Abu-Hamdeh, 2010). A recent study in Illinois showed that corn height was reduced due to compaction by high/standard inflation pressure tire systems in the first two years, while for soybean, the effect was significant in the third year (Shaheb, 2020).

Crop Vegetative Growth

Crops growing in compacted soils exhibited reduced morphological and physiological functions. The restricted root growth due to compaction might decrease leaf expansion and stomatal conductance (Lipiec & Hatano, 2003), crop growth, yield, and quality (Hassan et al., 2007; Chen & Weil, 2010). The most significant morphological effects of soil compaction in crops are stunted growth, reduced plant height and stem diameter, decreased nutrient uptake, reduced leaf gas exchange, and increased thickness of epidermal cells and cell walls (Clark et al., 2003; Grzesiak et al., 2013; Shah et al., 2017b). Decreased carbon assimilation, less translocation of photosynthates due to high mechanical impedance impacted the corn root system, which resulted in reduced growth of corn (Tubeileh et al., 2003; Shah et al., 2017b). High annual traffic intensity causes a significant reduction in soil aeration and limited oxygen in the root zone that results in a decrease in root and crop growth and yield (Hakansson, 2005; Chamen, 2011). The effect of soil compaction in Fig. 8 shows that compaction of soil is not only reduced plant height and growth of corn but also delayed its days to flowering (Dyck, 2017).

Crop Root Systems and Growth

Soil compaction can reduce root growth and development, and as a result, they impact crop productivity. But, its effect on crop growth and development is complex and can be influenced by axle load, tire inflation pressure (Abu-Hamdeh, 2010), dry, and wet weather conditions (Galambošová et al., 2017). Soil compaction impacts crop root length, its growth, distribution, and function (Ishaq et al., 2001b). Reduced plant growth and development were reported in soils with high strength (Rosolem et al., 2002; Gebauer & Martinková, 2005; Bengough et al., 2006). Root growth and development of canola and wheat were significantly reduced under wheel tracks (Chan et al., 2006). Soil compaction significantly reduced the length of seminal adventitious roots, total number, and length of lateral roots of both corn and triticale (Grzesiak, 2009). Soil PR values above 2.00 MPa showed restricting crop root development at varying degrees (Aase et al., 2001). Stunted root growth, poor root proliferation, and reduced availability of nutrients might be associated with a significant reduction in soil porosity, pore size, and soil aeration (Dexter, 2004; Nawaz et al., 2013). Soil

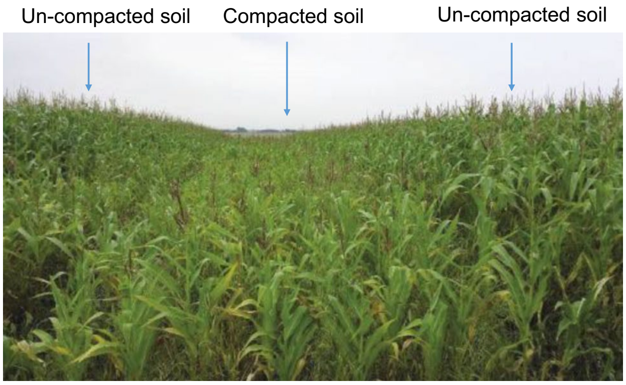

Fig. 8 Effect of soil compaction on corn growth and development in Ohio. Source: Fulton and Shearer, The Ohio State University cited by Dyck (2017)

compaction (BD 1.60 Mg m^{-3}) coupled with waterlogging had harmful effects on the root and shoot growth of wheat (Wu et al., 2018). Reduced growth and yield of potato (Stalham & Allen, 2001) and poor root system development in tomato (Tracy et al., 2012a), and reduced root dry matter (DM) of soybean were also observed due to soil compaction (Botta et al., 2010). High soil penetration resistance and mechanical injury to taproots of plants, and less nutrient availability due to soil compaction could be the reasons for reduced root growth in cover crops (Rosolem et al., 2002). The effect of compaction on the root length of some cereal crops is shown in Fig. 9.

Crop Lodging

Crop lodging results in decreased crop productivity. When the aboveground parts of crops are exposed to the storm, lodging occurs, which is mainly due to a poor root system. Crop yield losses due to lodging range from 3 to 25%, and in severe cases, it could be higher (Sui-Kwong et al., 2011; Shah et al., 2017a). Soil compaction resulting from conventional tillage caused a poor root system in corn that considerably increased lodging in heavy loamy soil (Bian et al., 2016). Depending on soil types, compaction had a positive impact on root system development in some crops. Soil compaction due to surface rolling in seedbeds resulted in increased soil strength and correspondingly increased plant emergence, root establishment, and growth of wheat (Atkinson et al., 2009). Higher resistance to lodging was observed in winter barley because of the greater anchorage strength of its root system (Scott et al., 2005). Improved contact between roots and surrounding soils in compacted areas (BD 1.50 Mg m^{-3}) increased root density and root diameter over less compacted soil (BD 1.10 Mg m^{-3}) (Tracy et al., 2012b).

Plant Nutrient Uptake

Soil factors such as PR, pore distribution, and water and nutrient availability had the most considerable effect on root growth (Hoad et al., 2001). Mechanical impedance restricts root growth, limits root access, and decreases the plant roots' ability to uptake nutrients (Passioura, 2002). This might also be due to an increase in BD and reduced pore size in soil (Nawaz et al., 2013; Sadras et al., 2016). Subsoil compaction caused a significant reduction in nutrient uptake by 12–35% for nitrogen (N), 17–27% for phosphorus (P), and up to 24% for potassium (K) in wheat, while in sorghum, the reduction of N, P, and K was 23%, 16%, and 12%, respectively (Ishaq et al., 2001b). As a result of decreased nutrient uptake, there were increased denitrification or leaching losses of applied nitrogen fertilizer resulting in reduced N efficiency (Lipiec et al., 2003a; Ruser et al., 2006; Gregorich et al., 2011). Low water infiltration and fewer macrospores account for reduced root growth and lower N uptake in compacted soil (Rosolem et al., 2002). Even though the storage and availability of N were greater in compacted soils, plant N uptake was restricted (Gregorich et al., 2011). Soil P is relatively immobile, and therefore, its uptake in compacted soil is mostly influenced by the root system architecture. The application of higher fertilizers rates to address lower crop yields increases the potential for nutrient loss. However, increased soil PR, decreased root distribution pattern, and root elongation ultimately lead to restricted root access to water and plant nutrients in compacted soil (Lipiec et al., 2012;

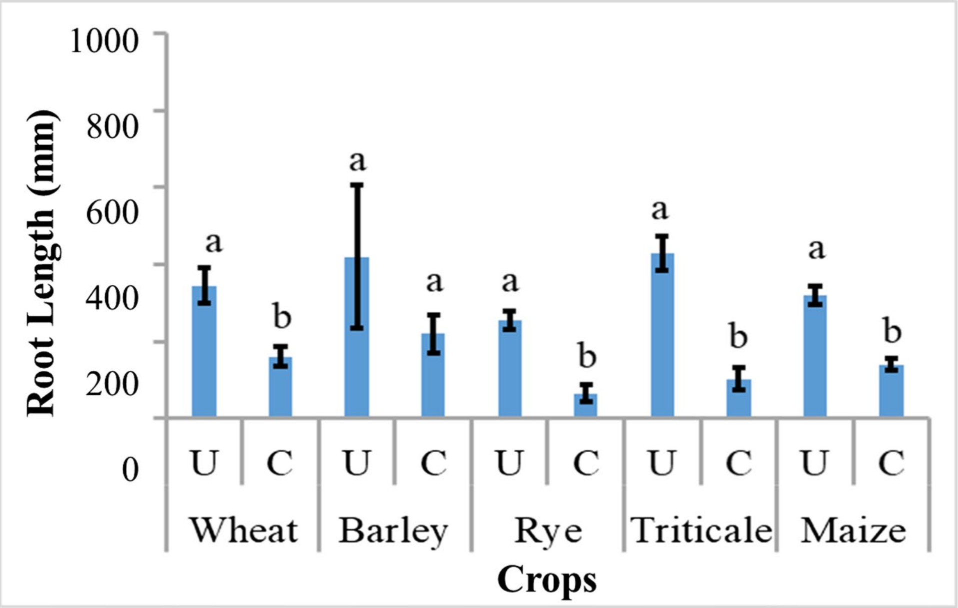

Fig. 9 Root length of cereals seven days after planting under un-compacted (U) and compacted (C) soil. Mean with the different letters within the same plant species are significantly different ($P < 0.05$). Adapted from Lipiec et al. (2012)

Nosalewicz & Lipiec, 2014; Siczek et al., 2015; Colombi et al., 2017).

Plant Water Uptake

Soil compaction reduces water infiltration rate, the number of soil pores, and total porosity, and thus, it may affect plants to access water and nutrient pools. High soil water content results in aeration problems. This slows drainage and accelerates to an anaerobic root environment, which in turn restricts nutrient uptake by plants (Dejong-hughes et al., 2001). Sudibyo (2011) reported that a decrease in water and fertilizer use efficiencies are the immediate consequences of soil compaction in conventional agriculture. Root density and water uptake from compacted clay loam soil are limited, suggesting that reduced water extraction may be rather a consequence than a cause for reduced plant growth (Amato & Ritchie, 2002). Besides, the plant's leaf area decreases with an increase in soil compaction even though there were no signs of a shortage of water or nutrients in the soil (Passioura, 2002). However, moderate compaction with soil BD of 1.50 Mg m^{-3} led to an increase in root water uptake in soybean, corn, barley, and rice (Lipiec & Hatano, 2003), while in wheat, it was 67% higher than heavily compacted soil with BD of 1.72 Mg m^{-3} (Nosalewicz & Lipiec, 2014). In response to increased topsoil PR, corn root systems become shallower, and water uptake from the topsoil increases (Colombi et al., 2018). However, drying of topsoil leads to further increase in the soil PR; consequently, it impeds root and plant growth, reduces water uptake, and crop productivity in corn (Colombi et al., 2018). In an 8-year study, Blanco-Canqui et al. (2010) showed that wheel traffic had a significant effect in decreasing water infiltration, soil water retention, plant-available water, effective porosity, and volume of pores (>50 µm). Stresses such as water deficits or soil compaction restricts crop rooting depth (Batey, 2009) and decrease the development of crop canopy and root systems' capacity and efficiency to capture and use resources such as water, carbon dioxide, radiation, and nutrients (Sadras et al., 2016). Water uptake of wheat decreased in response to the heavily compacted subsoil. However, the effects were partly minimized by increased water uptake from looser topsoil layers (Nosalewicz & Lipiec, 2014).

Effect of Soil Compaction on Biomass and Crop Yield and Economics

Soil compaction decreases biomass and crop yield by reducing crop growth and development. Studies in various soil types and environments showed that DM and yield of crops decreased significantly in compacted soils due to heavy machinery, higher axle load, and repeated field trafficking as compared to light equipment, lower axle load, and un-compacted soil (Voorhees, 2000; Ishaq et al., 2001b; Sidhu & Duiker, 2006; Chan et al., 2006; Abu-Hamdeh, 2010; Whitmore et al., 2011). Crop growth and productivity of corn decreased substantially due to soil compaction. Corn DM decreased by 26% and yield by 33%, respectively, and was attributed to adverse soil physical conditions resulting from compaction rather than limited N fertility (Gregorich et al., 2011). The effect of soil compaction, depending upon its severity and magnitude, can significantly reduce crop yields by 10 to 15% (Godwin et al., 2019). Subsoil compaction with vehicle axle load (11 Mg) followed by tillage caused a 15 to 43% reduction in corn yield (Voorhees, 2000), while 17% reduction was observed due to compaction caused by tillage with two-wheel passes (8 Mg axle load) and 300-kPa tire inflation pressure (Abu-Hamdeh, 2010). In a 5-year study conducted in a silty loamy soil in Kentucky, crop yield generally increased in soils subject to deep tillage at 400 mm. However, precision tillage treatments had a higher crop yield at the same depth compared to deep tillage at 400 mm at one site out of three study sites (Wells et al., 2005).

Crop response may vary due to dry and wet soil conditions. Results from a 17-year long-term study showed that yield reduction in subsoil compaction in clay soil was higher in wet seasons than in dry seasons (Alakukku, 2000). However, multiple machinery passes caused an approximately 33% crop yield loss in dry years compared to the single machinery pass (5%) in years when there was no shortage of soil moisture (Galambošová et al., 2017). Soil compaction due to heavy equipment (185 kN) caused severe grain yield reduction of soybean for three consecutive growing seasons (Botta et al., 2010). Crop yield loss has an impact on the profitability of farming systems. Decreased crop yield and less effective use of resources are the direct and indirect adverse economic effects of compaction (Botta et al., 2010; Chamen et al., 2015). Soils under the low incidence of compaction due to low tire inflation pressure had a higher crop growth and yield. As a result, there was a potential financial advantage compared to soils where compaction was caused by high tire inflation pressure (Stranks, 2006; Smith et al., 2014b; Shaheb, 2020). The effect of compaction on crop growth and yield in different farming systems are described in Table 1.

Effect of Soil Compaction on Draft Force Requirement and Fuel Use

Soil compaction influences the draft force and fuel use requirements of agricultural machinery. Besides soil degradation and soil erosion, soil compaction resulted in higher fuel consumption due to the higher rolling resistance of tires (Batey, 2009; Chamen et al., 2015). It is important to note that excessive fuel consumption depends on the machine

Table 1 Effect of soil compaction due to heavy machinery wheel traffic and tire inflation pressure on the growth and yield of crops under different soil types and locations

Crops (scientific name)	Soil types and locations	Tire inflation pressure/machinery traffic/axle load/soil strength	Key variables/parameters studied	Effects on crop growth and yield
Corn (*Zea mays*)	Silt loam, PA	700 kPa and 250 kPa; 10-Mg axle	PR, PE, Y	Reduced yield; an average of 17% in 3 years out of 4 (Sidhu & Duiker, 2006)
	Silty clay loam, NE; Vertisol, AUS; others	–	PR, RG, PP, PE, Y	Mechanical impedance restricts root growth (Hamza & Anderson, 2005; Raper & Kirby, 2006; Radford et al., 2007)
	Clay loam soil, ON, CA	14 Mg axle	PG, DM, Y	Reduced plant growth, DM (33%), and yield (26%), respectively (Gregorich et al., 2011).
	Garden soil, Cracow, Poland	BD 1.10, 1.34, and 1.58 Mg m^{-3}	BD, PR, RG, LWP, PTR, RR	Restricted root growth and greater damage in physiological characteristics such as reduced leaf water potential and photosynthetic and respiration rate in leaves (Grzesiak, 2009; Grzesiak et al., 2013)
	Silty clay loam, IL	0.14, 0.12, and 0.21 MPa for STP, and 0.07, 0.05, and 0.14 MPa, respectively, for LTP	PR, BD, soil MC, PE, PP, PH, EL, Y	Increased soil compaction, decreased growth, and 4.13 and 6.77% yield reduction in years 2 and 3, respectively (Shaheb et al., 2018; Shaheb, 2020)
	Silt loam, Slovakia	0, 1, and multiple passes and CTF; T—11.4 Mg, PT—5.5 Mg, CH—17.1 and 18.2 Mg	PR, BD, PH, EC, Y	Reduced crop yield by 7.5 to 25% (Galambošová et al., 2017)
Wheat (*Triticum aestivum*)	Sandy clay loam, Pakistan	BD 1.61 and 1.93 Mg m^{-3}	PG, Y	Decreased crop growth and Reduced yield by 8–38% (Ishaq et al., 2001a).
	Beijing, China/Lab study	High and low strength; 0.75 MPa	RG, BM	Impeded root growth and reduction in total biomass from 71 to 88% (Jin et al., 2015)
	Sodic brown clay, AUS	Wheel track and non-track; PR >2.0 MPa and BD 1.5–1.58 Mg m^{-3}	RG, Y	Reduction in root growth; no significant differences in yield (Chan et al., 2006).
	Silt loam, Slovakia	0, 1, and multiple passes and CTF; T—11.4 Mg, PT—5.5 Mg, CH—17.1 and 18.2 Mg	PR, BD, PH, EC, Y	Reduced plant height, ear count, and yield (5 to 9%) (Galambošová et al., 2017)
Soybean (*Glycine max*)	Clay soil, Argentina	Traffic intensity (0, 60, 120, and 180 Mg km ha^{-1}),	Y	Decrease in yield from 9.8 to 38% compared to zero traffic (Botta et al., 2004).
	Silty clay loam, IL	Same as corn	BMY, PE, PP, Y	Increased soil strength and decreased growth and 3.53% yield reduction in year 3 (Shaheb, 2020)

Table 1 (continued)

Crops (scientific name)	Soil types and locations	Tire inflation pressure/machinery traffic/axle load/soil strength	Key variables/parameters studied	Effects on crop growth and yield
Sorghum (*Sorghum bicolor*)	Sandy clay loam, Pakistan	Subsoil compaction; BD 1.61 and 1.78 Mg m^{-3}	PG, Y	Reduced crop growth. Decrease in yield by 14% in year 1 and d 24% in year 2 (Ishaq et al., 2001a).
Triticale (*Triticum secale*)	Garden soil, Cracow, Poland	BD 1.10, 1.34, and 1.58 Mg m^{-3}	RG, PC, LWP, P_n, PR	Major impact on root growth and physiological characteristics such as leaf water potential, photosynthetic and respiration rate in leaves impact relatively small (Grzesiak, 2009)
Potato (*Solanum tuberosum*)	Loamy sand, WI	Compaction with 29.8 and 26.2 Mg; PR >2.0 MPa	PR, RG	Limited root growth and crop establishment (Copas et al., 2009)
	Sandy soil, MN; silt loam, ID	PR > 3 MPa; BD 1.57 Mg m^{-3}	PR, BD, RG	Restricted root growth and stopped in severe cases (Aase et al., 2001)
Tomato (*Solanum lycopersicum*)	Loamy sand and clay loam, UK	BD 1.20 and 1.60 Mg m^{-3}	RA	Affects root architecture, influenced resource capture, and limited exploration of the soil volume (Tracy et al., 2012a)
Barley (*Hordium vulgare*)	Loomy soil	–	RG, Y	Root growth and yield decreased (Lipiec et al., 2003b)
	Sandy loam soil, Estonia	Axle load 4.84 Mg; 0, 1, 3, and 6 passes; PR 1.80–1.96 MPa	RDM	Reduction in root DM by 74% (Trükmann et al., 2008)
	Sandy loam soil, UK	0.12, 0.15 MPa (high) and 0.07 MPa (low)	MC, PR, BD, PE, PP, Y	Decreased yield approximately 25% in year 1 (Millington, 2019)
	Clay loamy soil, Jordan	5 and 15 Mg axle load; 200 and 400 kPa	PR, PE, Y	Higher inflation pressure and axle load decreased yield (Abu-Hamdeh & Al-Widyan, 2000).
	Silty loam, Slovakia	0, 1, and multiple passes and CTF; T—11.4 Mg, PT—5.5 Mg, CH—17.1 and 18.2 Mg	PR, BD, PH, EC, Y	Reduced plant height, ear count, and yield 9 to 33% in 2012 and 8 to 13.4% in 2014, respectively (Galambošová et al., 2017)
Radish (*Raphanus sativus*)	Elsinboro and Galestown series, MD	Axle load 11.88 Mg with 0, 1 and 2 passes; 5.83 Mg with 0 and 1 pass	RDM, BM	Reduction in root DM by 31% and biomass by 31.3%, respectively (Chen & Weil, 2010)
Rapeseed (*Brassica napus*)	-do-	-do-	RDM	Reduction in root DM by 50% and biomass by 62.89%, respectively (Chen & Weil, 2010)
Rye (*Secale cereale*)	-do-	-do-	BM	Total biomass decreased by 32.01% (Chen & Weil, 2010)
Canola (*Brassica napus*)	Sodic brown clay, AUS	Wheel track vs. between the wheel tracks; >2.0 MPa; 1.5–1.58 Mg m^{-3}	RG, Y	Reduction in root growth and potential yield by 34% in the wheel tracks (Chan et al., 2006).

Table 1 (continued)

Crops (scientific name)	Soil types and locations	Tire inflation pressure/machinery traffic/axle load/soil strength	Key variables/parameters studied	Effects on crop growth and yield
Oat (*Avena sativa*)	Sandy clay, UK	LTP, RTF, and CTF	Y	Reduced oats yields by 25% in RTF in year 2 (Millington, 2019)
Cotton (*Gossypium hirsutum*)	Silt loam, AK	CL, CDB, CC, and CNT 2.14–2.86 MPa	PR, ECt, green NDVI, Y	Reduction in yield in the third year from 17 to 22% over control (Kulkarni et al., 2010)

BD bulk density, *BM* biomass, *CL* control, *CC* sub- soiled and compacted (by running a backhoe, 6.7 Mg, once on sub-soiled plots), *CDB* conventional (subsoiled, disked, and bedded), *CH* combine harvester, *CNT* compacted only (by running a backhoe ten times), *CTF* controlled traffic farming, *DM* dry matter, *ECt* ear count, *EC* electrical conductivity, *EL* ear length, *LWP* leaf water potential, *LTP* low tire inflation pressure, *MC* soil moisture content, *NDVI* normalized difference vegetation index, *PE* plant emergence, *PG* plant growth, *PH* plant height, *Pn* photosynthetic rate, *PP* plant population, *PR* penetrometer resistance, *PT* planting tractor, *PC* physiological characteristics of leaves, *RA* root architecture, *RG* root growth, *RR* respiration rate, *RTF* random traffic farming, *ST* shallow tillage, *T* tractor, *Y* yield

width, speed, size and weight of equipment and type and size of tires, tire inflation pressure, and time needed for field operations (Botta et al., 2010; Battiato et al., 2013). Increased fuel consumption and decreased work rate were reported due to field traffic with heavy equipment (185 kN, 9.5 L ha^{-1}) as compared to the light equipment (127 kN, 6.5 L ha^{-1}) (Botta et al., 2010). Heavier tractor (180 HP) consumes around 38% more diesel (25 L h^{-1}) than a 120 HP tractor (18 L h^{-1}) (Nix, 2011). Subsoiling is used to remove soil compaction, but deep plowing results in loosened soil, which increases the risk of re-compaction of the subsoil (Soane et al., 1986).

Furthermore, managing compacted soil involves higher costs. As a result, energy consumption for tillage operations to manage compacted soil can be increased by 200–300% (Godwin et al., 2019) and 25–40%, and half of tractor engine power was reported to be wasted (Tullberg, 2000; Tullberg et al., 2007). Consequently, soil compaction caused increased use of energy, cost, and risks of re-compaction, further deteriorating soil conditions, and caused additional adverse environmental consequences.

Management Strategies to Alleviate Soil Compaction

Improved root distribution and increased rooting depth are vital for better crop growth and yield. By following good soil management practices, which help with efficient uptake of applied nutrients by crops, growing deep-rooted crops in rotations and conservation tillage may help avoid or alleviate compaction. Prevention of soil compaction is far better than correcting compaction problem after it occurs (McKenzie, 2010), meaning it will be a win-win situation for improving farm productivity while simultaneously reducing environmental impacts (Hallett et al., 2012). However, the most commonly used strategies in minimizing compaction are avoidance, alleviation, subsoiling, controlled traffic, and acceptance (Dejong-hughes et al., 2001; Hamza & Anderson, 2005; Botta et al., 2010). A comparison of the effect of compaction management and gross margin is shown in Fig. 10. Reducing wheel load, e.g., using dual or tandem wheels, high flexion tires, and reducing tire inflation pressure, may reduce the risk of compaction (Keller & Arvidsson, 2004; Shaheb, 2020; Shaheb et al., 2021). Reducing tire inflation pressure has shown a positive effect on maintaining soil porosity and increased crop growth and yield (Smith et al., 2014b; Shaheb et al., 2018, 2020; Millington, 2019). Subsoiling contributed to a significant reduction of compaction and resulted in increased root growth of cotton and cover crops and cotton yield (Schwab et al., 2002; Busscher & Bauer, 2003). Deep tillage with vehicle axle loads ≤10 Mg and tire inflation pressures <250 kPa

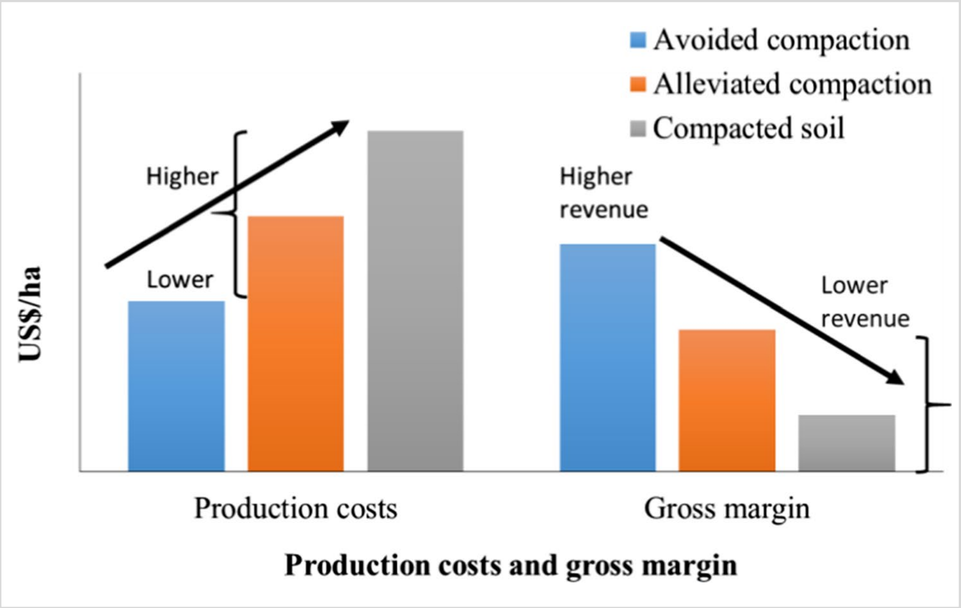

Fig. 10 A typical comparison of different compaction management strategies and their effect on gross margin of crops. After Chamen et al. (2015)

effectively reduced soil compaction (Sidhu & Duiker, 2006). Detailed management strategies for dealing with soil compaction are described in Table 2.

Conclusions

Soil compaction is unfavorable for sustainable agriculture. It decreases the volume of a given soil mass by reducing the air-filled pore space. Soil compaction changes soil structure by increasing bulk density and penetration resistance and decreasing the total porosity of the soil. Use of heavy machinery for tillage operations, planting, pre- and post-emergence spraying of crop protection chemicals, and harvesting crops can cause soil compaction. These field operations with high gross weight vehicles/machinery eventually can damage soil structure and deteriorate soil environment that are critical for sustainable crop production, leading to reduced crop growth and yield. Soil compaction alters plant root architecture and anchorage. As a result, reductions in plant nutrient uptake and growth are observed, resulting in a reduction in biomass and crop yield. Soil compaction resulting from the multiple passes of heavy machinery, with various combinations of wheel load and ground pressure, supports the following theoretical predictions: (a) high ground pressure significantly increases soil BD of topsoil but has less effect at greater depth and (b), conversely, increases in vehicle/wheel load, at a given ground pressure causes significant increases in compaction at deeper depths.

Compaction of soil results from the conventional vehicles and its subsequent effect on altering soil structure and reducing crop development exemplifies the significance of lowering gross vehicle weight to minimize soil compaction. Use of appropriate machinery for field operations, subsoiling, tracked vehicles, and site-specific deep tillage treatment could reduce soil compaction. High flexion tires operated at lower inflation pressures increase the tire-soil contact area, and when coupled with the appropriate tillage systems can reduce soil compaction. Crop rotation with deep-rooted and cover crops (e.g., creation of bio-drilling by the decomposition of roots) and conservation agriculture practices can play an important role in reducing soil compaction, which results in increased pore volume to support proper root development and access to nutrients. The current literature review summarized here will help to better understand the causes and effects of soil compaction arising from the use of heavy machinery, improper tire inflation pressure, and field trafficking on soil properties, crop growth and development, yield, and farm income. It will also assist in improved understanding of soil compaction and provide useful information to growers, ranchers, researchers, and policymakers to support better decisions on reducing the impact of soil compaction in production agriculture.

Future Research Needs

Mechanization is an integral part of modern and intensive agriculture. Additional research on reducing soil compaction, and ameliorating of compacted soils is needed to minimize soil and ecosystem disturbance and maximize crop productivity. Comprehensive research on compacted and uncompacted layers in the soil profile across different soil types and environments, both for shallow and deep-rooted crops, is required. Studies on new tires technologies with low and high inflation pressures for machinery of varying axle loads and suitable cultivation practices on, benefits to

Table 2 List of management strategies to alleviate or minimize the risk of soil compaction in crop production

Management strategies/measures	Key characteristics	References	Notes/remarks
1. Avoidance	Options, e.g., use of high flexion tires; tracked vehicles, or CTF.	(Dejong-hughes et al., 2001; Gregorich et al., 2011; Chamen et al., 2015).	Use of light equipment; conservation tillage may also be an option.
2. Controlled traffic farming	30% less area trafficked. A predetermined wheelways are used to run the equipment.	(Ishaq et al., 2001a; Tullberg et al., 2007, 2018; Chamen, 2011; Antille et al., 2015; Galambošová et al., 2017; Godwin et al., 2017)	Equipment widths and wheel track spacing to be matched; RTK guidance required.
3. Reducing the weight of machinery/axle/wheel load	Less compaction resulted in increased crop performance.	(Keller & Arvidsson, 2004; Hamza & Anderson, 2005; Schjønning et al., 2008; Botta et al., 2010)	Timeliness of operation is an issue.
4. Deep tillage/deep ripping/subsoiling and chiseling	Loosened soil; sometimes cause damages to soil structure.	(Ishaq et al., 2001a; Schwab et al., 2002; Busscher & Bauer, 2003; Sidhu & Duiker, 2006; Radford et al., 2007; Abu-Hamdeh, 2010; Botta et al., 2010)	Risk of re-compaction (Chan et al., 2006); draft and fuel wastage.
5. Use of low ground/inflation pressure tires/high flexion tires	More tire footprint, less compaction, fuel consumption, and payback period.	(Ansorge & Godwin, 2007, 2008; Schjønning et al., 2008; Godwin et al., 2017; Millington, 2019; Shaheb, 2020)	Higher tire price and sometimes longevity is an issue for farmers.
6.Introduction of rubber tracks on track tractors	High tractive efficiency; less fuel consumption.	(Ansorge & Godwin, 2007, 2008, 2009; Schjønning et al., 2008; Arvidsson et al., 2011; Molari et al., 2012)	High internal resistance and may reduce traction efficiency.
7. Agronomic practices (e.g., crop rotation with deep tap-rooted crops)	Bio-drilling/creating root channels.	(Ishaq et al., 2001a, 2001b)	Field operations often damage soil structure and root channels.
8. Conservation tillage	Less disturbance of soil; increased infiltration.	(Ishaq et al., 2001a; Raper & Kirby, 2006; Fonteyne et al., 2019)	Soil compaction often increased; lower yield
9. Site-specific management and variable depths tillage	Reduced energy cost; decreased fuel consumption.	(Raper et al., 2000; Mzuku et al., 2005; Wells et al., 2005)	Status of soil compaction to be known; large scale focus is limited.
10. Cultivation of cover crops, especially deep-rooted crops	Add OM; reduce soil erosion and compaction.	(Kaspar et al., 2001; Williams & Weil, 2004).	–
11. Mulching, e.g., straw mulching	Increased OM and preserved soil moisture.	(Siczek et al., 2015)	–
12. Ecosystem services (e.g., pollination and biological nitrogen fixation)	Provided biodiversity above and below grounds.	(Bommarco et al., 2013; St-Martin & Bommarco, 2016)	–
13. Using a biological method, e.g., *Arbuscular mycorrhiza* (plant symbiotic fungi)	Increase root growth; nutrient uptake, e.g., P; maintain soil biological communities.	(Miransari et al., 2007, 2009b, a).	Effects may vary; Need further field-scale studies.
14. Natural freezing and thawing events	Soil compaction may be reduced. More evident in the subsoil.	(Voorhees, 2000; Etana et al., 2013)	Natural processes: the effect may vary.

the ecosystem are urgently needed. Future research needs to focus on sensor development for measuring ingand quantifing the spatial and temporal distributions of soil compaction, and its management. Investigation of undisturbed and disturbed soil profiles using X-ray computed tomography tool could provide a detailed understanding of the effect of soil compaction and alteration of soil structure. With the advances in precision agriculture and application of remote sensing tools for compaction assessment and mapping; modeling of soil compactiona and management, and optimization of soil-machine-crop systems are warranted. Further research is needed to focus on developing crop varieties and hybrids with desired root characters that penetrate the soil, anchor the plant and access water and nutrients to support crop grow in compacted soils.

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Declarations

Conflict of Interest The authors declare that there is no conflict of interest.

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