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Soil compaction and their management in farming systems: A review

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Abstract
Soil compaction is a thoughtful and preventable kind of soil degradation that can outcome in increased soil erosion and reduced crop production. It is the disturbance and lessening of the macro pores within the soil and was one of the major problems facing current farming. The overdoing of machinery, exhaustive cropping, short crop rotations, intensive grazing and unsuitable soil management leads to compaction. Soil compaction rises in a wide range of soils, climates and is aggravated by low soil organic matter content and use of tillage or grazing at great soil moisture content. The direct impacts on soil physical properties such as increases soil strength and decreases porosity, structural stability, soil hydraulic conductivity, nutrient availability and decreases soil health. The several soil compactions induce root bend, underdeveloped shoot growth, low and late germination rate, and great mortality rate. A harmful sequence before occurs of condensed plant growth leading to lesser inputs of fresh organic matter to the soil, cheap nutrient recycling and mineralisation, decreases soil biodiversity through decreasing microbial biomass, enzymatic activity, soil fauna and flora and increased wear and tear on cultivation machinery. Several approaches are requiring proposing the declaration of the soil compaction tricky is realistic consenting to the soil, environment and agriculture system. These techniques was developed to escape, adjournment or prevent soil compaction: (a) decreased on pressure in soil either by reducing axle load or increasing the contact area of wheels (b) operational soil and allowing grazing at optimal soil moisture content, soil texture , soil structure, and soil organic matter (c) decreasing the number of passes via farm machinery and the intensity and frequency of grazing; (d) restraining traffic to certain areas of the field or controlled traffic (e) improving soil organic matter through retaining of crop and pasture residues; (f) eliminating soil compaction by deep ripping in the presence of an aggregating agent; (g) crop rotations that comprise plants with deep, strong taproots (h) conservation of an appropriate base saturation ratio and complete nutrition to meet crop requirements to help the soil, crop system to resist unsafe external stresses. Proper management techniques can minimize the influence of compaction, but improved management is the best elucidation for addressing compaction.

Keywords: Soil compaction, tillage, controlled traffic, no-tillage, animal grazing, plant roots

1. Introduction
Soil compaction can be the disruption and lessening of the large pores within the soil. The presence of extra soil moisture at the time of any field operation is the foremost aspect leading to soil compaction. The construction purposes, a compacted soil is the perfect but under normal crop production, a compacted soil can be a serious problem. Penetration into the soil by tillage implements and crop roots is restricted. Soil compaction can also be one of the underlying agents of soil erosion, nutrient lessening and pollution which are key issues brought up in many recent reports by the UN and other international organisations (Hartemink, 2008) [30]. It is also important to be aware that soil compaction is a phenomenon associated not only with agriculture, but also with forest harvesting, amenity land use (e.g. localized trampling), pipeline installation, land restoration and wildlife pathways. Soil compaction is not a recent phenomenon. It was encountered in the form of ploughpans long before the advent of mechanized agriculture. Current farming techniques, however, exacerbate the risks. Stalham *et al*. (2005) [77] reported that the point out that there has been a major change in the methods of cultivation for potatoes which has increased rather than decreased the risk of creating poor soil conditions, including compaction.
The axle weight of tractors, harvesters and trailers has increased and the impact assessed (Van den Akker *et al*., 2003; Godwin *et al*., 2008) [83, 26]. This increased weight, although mitigated by controlling tyre pressures, is a matter of major concern.

Tillage operations are done by using heavy machines with high axle load, wheel slip, and ground pressure thus impinges on soil physical properties. Conventional tillage relied on heavy soil opening and non-site specific wheeling result in reduction of macropores led to soil hardening under tilled layer. Moreover, Botta *et al*. (2007) [8] 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) [43]. 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.

Soil compaction is the impacts on crops and soil properties are complex and then the state of compactness is an essential soil structural feature, there is a need to find a parameter for its characterization, such as relative bulk density, that provides directly comparable values for all soils (Hankinson and Lipiec, 2000) [27]. Since soil bulk density is the mass of dry soil per unit volume, then the relationship between soil compaction and its capacity to store and transport water or air is obvious. For this reason the dry soil bulk density is the most frequently used parameter to characterize the state of soil compactness (Panayiotopoulos *et al*., 1994) [54]. However, in swelling or shrinking soils the bulk density should be determined at standardized moisture contents, to prevent problems caused by water content variations (Hankinson and Lipiec, 2000) [27]. Soil strength is used for soil compaction because it reflects soil resistance to root penetration. Soil water infiltration rate also can be used to monitor soil compaction status, especially of the topsoil. Water infiltrates uncompacted soils that have well-aggregated soil particles much faster than massive, structure-less soils (Hamza and Anderson, 2003) [28].

The most recent focused only on practical soil management matters and soil compaction on biogeochemical processes and biodiversity, both at macro- and microscales. Furthermore, existing models for the soil compaction are critically discussed and new directions for modelling the effects of the soil compaction on the soil are being proposed. The current paper are discusses in the context of the current situation, the causes, identification and effects of compaction and also its alleviation. The over-compaction subsequently the compactness of soil covers a range of conditions from loose or under-consolidated, through an optimal state to an adverse condition. Over-compaction can be regarded as a universal phenomenon found in all systems of mechanised land use and also where land is trampled by people, livestock or wildlife. The concept of optimum level of compaction is important, especially in controlled traffic system where any external source of compaction is evaded because it might cause a suboptimal level of compaction and yield despairs.

2. Causes of soil compaction

The soil compaction is a natural phenomenon caused by freezing are drying or artificial phenomenon caused by mechanical processes (Fabiola *et al*., 2003). The conventional farming systems practices containers also degrade the soil by the soil compaction. In the modern agriculture, most of the field operations from sowing to harvesting are done mechanically by using heavy wheeled machines which can compact the soil at every passage (Williamson and Neilsen, 2000). The soil compaction by a machine, in general, depends on the soil strength and loading of machine (Alakukku *et al*., 2003). The soil strength is influenced through the organic matter, water content, soil structure, and texture while the loading is expressed by axle load, number of tyres, tyre dimensions, tyre velocity, and soil tyre interaction (Sakai *et al*., 2008). Axle load should not be confused with axle pressure as axle load is weight of machine (kilogram) while pressure is the axle load per unit surface area (kilopascal) and in the soil compaction. Aggregate the pressure on the soil increases the chances of the soil compaction. Increasing the frequency of passages of machines over a soil increases its dry bulk density and cone index resulting in the top soil compaction and unsuitable physical soil conditions for seed emergence (Sakai *et al*., 2008). However, a major portion of the total soil compaction is caused by the first passage or early passages (Sakai *et al*., 2008) of the machine and 10 passes can affect the soil up to 50 cm depth (Hamza and Anderson 2005) [29].

Animal trampling fire cause the soil compaction and can degrade the soil structure (Silva *et al*., 2003) [22]. The soil compaction caused by grazing animals through hoof action is likely to be more widespread within the paddocks as compared to the soil compaction caused by mechanical implements which is limited under the tracks (Sigua and Coleman, 2009) [70]. Physical deterioration by grazing animals depends on the trampling intensity, soil moisture, plant cover, land slope, and land use type. Animal caused the soil compaction could range from 5 to 20 cm and might affect the soil bulk density, hydraulic conductivity, macropore volume, and penetration resistance of the soil (Sigua and Coleman, 2009) [70].

In contrast to the cultivated lands, harvesting operations in forest cause more soil compaction because of: (1) the use of heavy machinery for harvesting; (2) felling, pushing, pulling, and lifting of logs; (3) during transport of logs that exert a combined pressure on the soil; (4) no tillage operations in forests to loosen the soil. In the forests, harvesting operation causes different types of the soil disturbances and probability of the soil compaction is directly related to harvesting system and harvesting density (Sowa and Kulak, 2008) [76]. The use of light weight multifunctioning machines can reduce the passages and ultimately the degradation of the soil (Radford *et al*., 2000) [58].

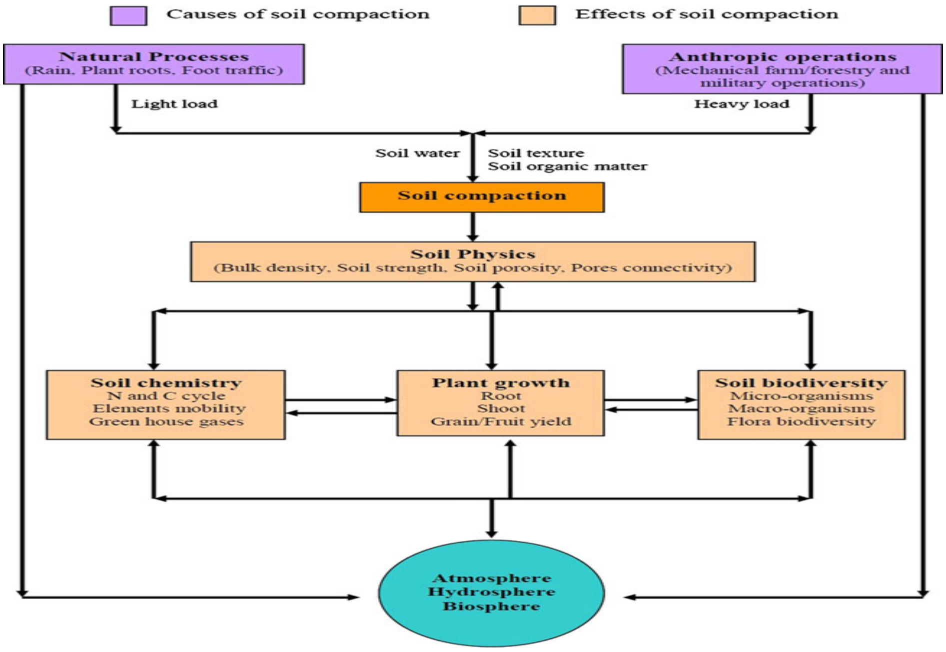

Fig. 1 Causes and effects of soil compaction and their on soil physical properties with ultimate direct effects on soil chemistry, plant growth and soil biodiversity compartments

In the urban areas, urban parks and recreational sites receive large number of visitors and with increasing urban population, visitors' pressure on these sites is increasing day by day (Frick *et al*., 2007) [24]. Trampling effects of the visitors on the soil and vegetation have been reported by many authors (Sarah and Zhevelev, 2007) [68] and these effects are long term in some cases (Kissling *et al*., 2009) [35]. Increasing visitors' pressure results in the soil compaction, increased bulk densities, decreased soil porosity and decreased organic matter contents. Military operations or military training exercises in the past have also resulted in severe soil compactions in some places (Silveira *et al*., 2010) [73] and increased bulk density of the soils up to 2.12 Mg/m^3 has been reported due to military operations (Webb, 2002) [85]. Natural causes (tree roots, precipitation, seasonal cycles, etc.) of the soil compaction are not as harmful as anthropogenic causes: the soil compaction associated with natural causes is limited in top 5 cm of the soil and the soil compaction due to the trampling and urban pressure on a site can compact the soil up to 20 cm while mechanical operations can compact the soil up to 60 cm.

3. Impact of soil compaction on soil properties

3.1 Effect of bulk density on soil compaction

Bulk density is defined as the oven dry mass of soil per unit volume. Good soil structures are described by increased in soil macro aggregates and porosity. The bulk density is increase with increase in soil compaction, as compacting forces squeeze the volume of soil via eliminating pore spaces. The external stress means high axle load is diminishes soil aggregation, thus increasing buildup density of soil. It is well recognized that upsurge in bulk density affected decline in yield in Argentina. Ressia *et al*. (1998) [61] described that if bulk density >1.2 mg m^{-3} ensued in 30% decrease in maize yield. Another significance associated with improve in bulk density might be due to compaction is high penetration resistance, fewer infiltration, great runoff, and more soil erosion. The number of passing also affects the extent of bulk density. Under different tillage regimes, bulk density varies, as conventional tillage initially occasioned in high porosity and low bulk density in early season, whereas later on due to compaction-causing agents, the number of pores decreases and bulk density increases, could be prolonged (Yavuzcan *et al*., 2000) [89]. Nevertheless, 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.

The soil compaction is significant decrease in soil porosity and soil aeration, roots show stunted growth and poor root proliferation (Dexter, 2004) [19]. 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. Several studies revealed that soil compaction initiated substantial yield reduction in many crops (Botta *et al*., 2002) [8]. Soil compaction decreases plant growth by reduction of the development of plants. Moreover, Montagu *et al*. (2001) [48] reported that the less seed germination and reduced early root growth in compacted zone which might be described to reduce nutrient uptake and poor aeration. However, seed germination in compacted soil also depends on clay contents and soil moisture level. Poor seed germination and stunted root growth in compacted soils having high clay contents under dry climate was renowned. 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) [65].

3.2 Effect of porosity on soil compaction

Soil consists of three kinds of pores which are micropores, mesopores and macropores in soil. The airs are filled macropore in soil in which supply oxygen to soil fauna and flora. The decrease in macropores occasioned in the development of anoxia conditions and interferes with crop growth and development. The soil compaction diminishes the pore spaces and consequently checks the transfusion and passage of air and water within soil profile and also water retention characteristic (Dexter, 2004) [19]. The alteration in the pore size distribution due to compaction ensued in increased runoff, reduced infiltration, and great erosion losses. The weighty use of farm apparatuses enforced high axle load and ground pressure on the soil, producing shrinkage in pores, consequently, and volume of pores reduced (Pagliai and Vignozzi, 2002) [53]. The tillage systems which are conventional tillage, widespread releasing of soil progresses more macropores at the beginning season, whereas future on, macropores became condensed due to soil compaction. The structural instability of the pores is extremely dependent to timing, intensity of field traffic, and rainfall pattern and tends to change with alteration in these reasons (Karunatilake and van Es, 2002) [33]. In the influence of frequent wheeling on pore size distribution and pore volume, they further noted that no visible macropores were perceived in highly compacted zone (Boizard *et al*., 2013) [7]. Furthermore, enormous soil structure disturbance and smooth breaking surface are also established in this zone (Fig.2). The obliteration influence of compact zone has compacted zone harmfully affects macropores 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 (Koch *et al*., 2008) [36].

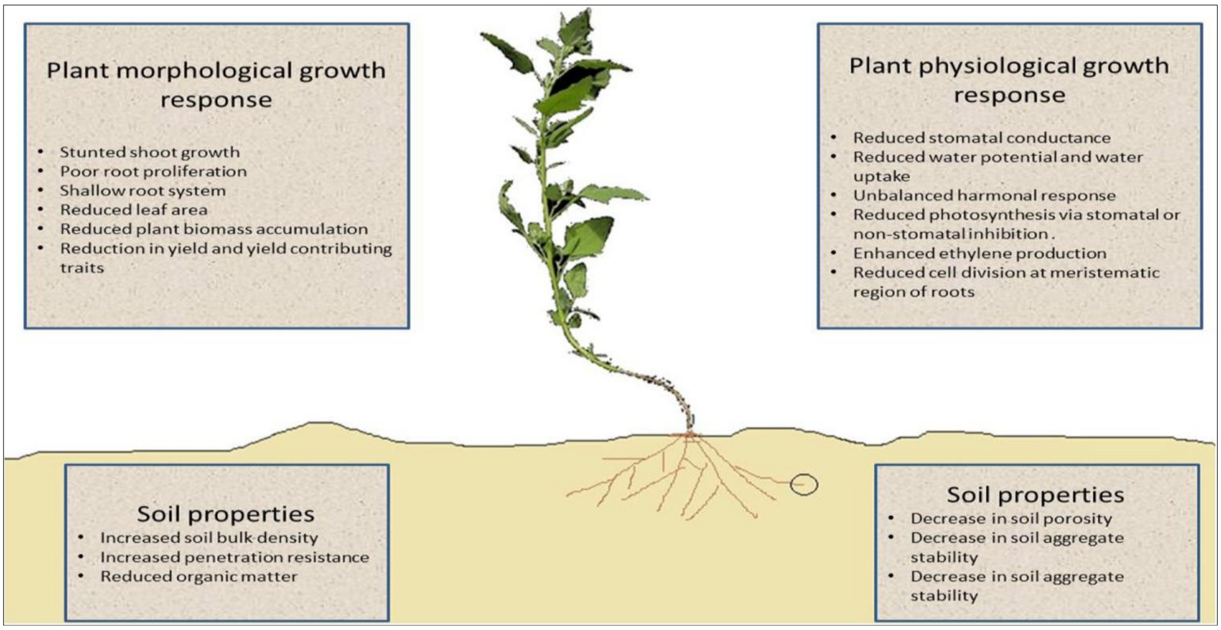

Fig. 2 Summary of the knowledge of the effects of soil compaction on soil plant morphological and physiological growth and soil properties.

3.3 Effect of soil moisture content on soil compaction

Soil moisture content is the most prompting factor that makes soil susceptible to compaction, as penetration resistance upsurges and soil water potential declines (Lipiec *et al*., 2002) [41]. The rising soil moisture content causes reduction in macropore spaces and leads to decline in load support capacity of the soil and permissible ground pressure (Kondo and Junior, 1999) [37]. Additionally, contribution of soil water content towards soil compaction is dependent on deformability of soil, pre-compression 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 dry soil the lower will be stress transformation and the lower will be de-formation in soil structure (Batey, 2009) [6]. 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 con-tent, causing compaction to deeper in soil profile. Depth and width of compacted zone are governed by high moisture content, causing low structural porosity and high structural deformation. It is well known that decline 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) [46]. The 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 com-parison and calculation of soil moisture content, determination of liquid, plastic, and solid limits of soil might be a better scale (Quiroga *et al*., 1999).

3.4 Effect of hydraulic conductivity on soil compaction

The hydraulic conductivity is largely saturated for highly sensitive to soil deformation, particularly soil compaction and alteration in the porosity of soil (Matthews *et al*., 2010) [45]. Reduction in the soil aggregate stability, bulk density in soil is increased and lessening air voids ending in decrease in hydraulic conductivity of soil (Nayak *et al*., 2007). The upsurge in soil strength due to soil compaction also diminishes hydraulic conductivity (Radford *et al*., 2000) [58]. Saturated hydraulic conductivity is the main function of structural dissemination of pores, more vulnerable to lessening than unsaturated hydraulic conductivity. 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. Soils having more micropores have high saturated hydraulic conductivity than soils with more macropores.

The degree of alteration in hydraulic conductivity differs with dissimilar soil depths even within the same soil profiles. They also found that changing values of conductivity at top soil were associated with mean value while of subsoil were very near to bulk density curve. This implies that bulk density is high in subsoil compaction than in top soil and consequently, reduction in hydraulic conductivity occurs in the same approach.

3.5 Effect of structural stability on soil compaction

Soil is a heterogeneous structure, comprising of three dimensional arrangements of primary particles, organic matter and allied pores forming soil aggregates. Soil structural stability or aggregate is a key indicator of soil structure and is a fundamental property that determines its productivity and resistance to soil erosion and degradation. It is an important index of soil quality, and soil physical properties affect soil productivity and sustainability. Soil aggregates are actually groups of soil particles that stick together as outcome of cohesive forces among particles and interaction of organic matter, cations, and anions with soil particles. Soil with high stability index is more productive, produces higher crop yield, while with low stability index, soil erosion loses are high. Soil compaction reduces formation of soil aggregates; it becomes worsen when high axle load and high moisture content together assaulted on soil. Heavy tillage, high axle load, ample moisture, rutting action of tire, and velocity and intensity of wheeling affect the soil aggregate stability. The alteration of aggregate stability is an early indication of soil degradation or deterioration quality. Among tillage systems, conservation tillage system resulted in high structural regeneration and aggregate formation than conventional tillage system (Alakkuku *et al*., 2003) [1]. 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) [86]. Pagliai and Vignozzi (2002) [53] reported that the dense tillage together with moisture reduces volume of pores, and consequently, soil aggregates pushed together and their structures become fragmented and altered in non-accommodating shapes. Compacted soil is characterized by little pore spaces and small soil aggregate stability index occasioned in reduced infiltration and increased runoff. Sandy soils have more dispersed particles with less aggregate stability and destructive impacts on clayey soils as they have more binding of soil aggregates than sandy soils.

3.6 Effect of penetration resistance on soil compaction

The penetration resistance is produces the work done by root to enter in the soil (Braim *et al*., 1992) [13]. The greater mechanical insolence is greater will be compaction, outcomes in higher penetration resistance, which results in more work done by roots. Soil property is widely employed to compute the degree of changes in the soil porosity and aggregate stability (Dexter *et al*., 2004) [19]. The soil compaction is affected by significant increase in penetration resistance. The penetration resistance increases with increase in bulk density and lower soil water potential and root penetrability reduces with increase in penetration resistance. The lessening in penetration level is directly associated with proliferation in water potential. Dry soils have more penetration resistance in the presence of high soil water, low soil strength and penetration resistance (Lipiec *et al*., 2002) [42].

3.7 Effect of soil strength on soil compaction

The soil strength or resistance to penetration is used for measured through soil compaction (Bouwman and Arts, 2000) [11]. The soil strength rises with increasing bulk density while it decreases with decreasing soil moisture content. One should be watchful when measuring penetration resistance because it varies between the seasons due to different moisture contents (Bouwman and Arts, 2000) [11]. The soil strength is measured by a penetrometer (Usowicz and Lipiec, 2009) and, furthermore, cone penetrometer is widely employed (Yu and Mitchell, 1998) to measure the soil strength in terms of cone resistance (megapascals). The cone resistance larger than 3 MPa caused a major hindrance for the root penetration of four tree species (Japanese larch, Italian alder, birch, and Corsican pine) in the sandy loam soils as shown in (Fig. 3) nearly all roots (90.7%) were present in the soil with a cone resistance class less than 3 MPa (Sinnett *et al*., 2008) [74].

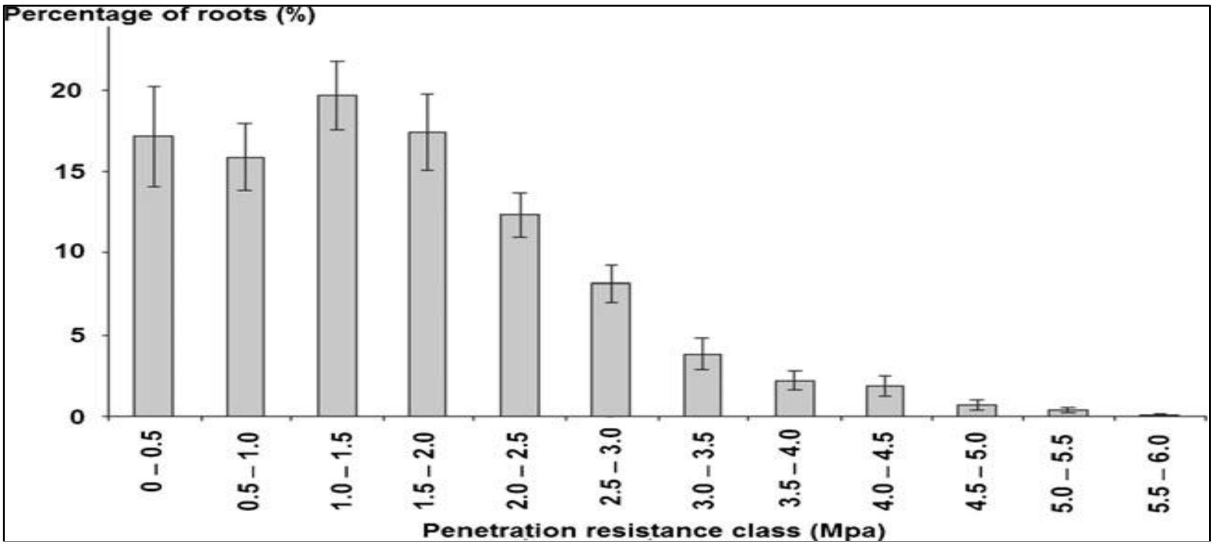

Fig. 3 Average percentage of roots in each penetration resistance.

The soil moisture is a significant factor for measuring the degree of compaction upon trampling where the deleterious impact of livestock trampling generally increases as the soil moisture at the time of trampling increases and grazing should be strictly prevented on wet soils. The aggregate size was reduced due to attributable to the mechanical shearing action of trampling at less soil water when the structure of the grazed soil became less stable. The grazing effects on soil structural stability were significant only in the periods when the soil dried, and it was suggested that stocking rates must be regulated in those dry periods. The grazing impacts on soil structural stability were substantial only in periods at what time the soil dried, and it was suggested that stocking rates must be regulated in those dry periods. However, some workers have reported that animal trampling did not show a significant effect on soil physical properties. Ballenger (2001) found that, although the differences in soil strength data between grazed and un-grazed sites were statistically significant (Fig. 4), these differences were not large enough to influence plant growth.

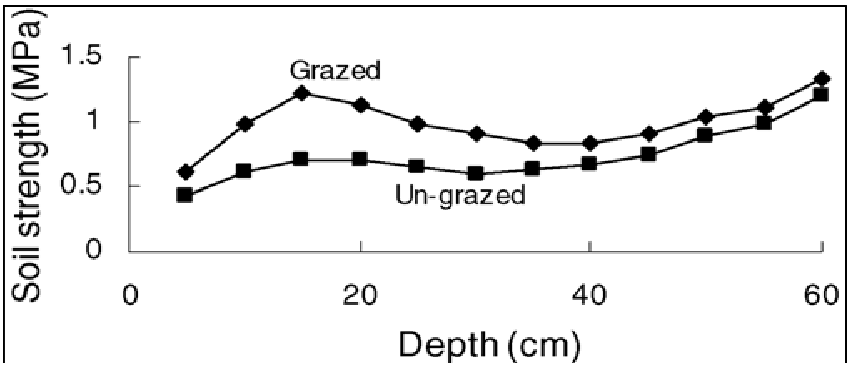

Fig. 4: Average soil strength for grazed and un-grazed sandy soil (Ballenger, 2001).

3.8 Effect of soil organic matter on soil compaction

Organic matter is the decomposition of plant and animals residues which increase soil fertility. The adequate and sustaining amount of organic matter in the soil stabilizes soil structure and makes it more resistant to soil degradation and reduce bulk density and soil strength (Carter, 2002) [15]. Organic matter in soil plays significant role in preserving soil biological activities. High soil organic matter outcomes 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) [88]. The avoiding action of organic matter could be due to observed 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. Likewise, organic matter residues on soil surface have been exposed to mitigate the effects of soil compaction (Hamza and Anderson, 2005) [29]. A significant layer of soil layer of surface crop residues could be beaten action under squeezing of heavy machineries, but they can retain their shape and structure once the traffic has passed. The 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 surface, as this organic matter attached to soil particles especially clay particles and binds micro and macro-aggregates soil, thus preventing soil from become compacted by the action of heavy machines. Finally, soil organic matter is a very important soil property, which can determine the greatness of soil compaction.

4. Impact of soil compaction on mechanized farm operations

4.1 Effect of mechanical load on soil compaction

The agricultural operations is compulsory the use of heavy machinery during tillage and interculture or fertilizer application. The continuous increases in the weight of farm machinery and the necessity to use heavy machines have 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 (Smith *et al*., 1997) [75]. The vulnerability of soil to become compacted has been observed as an interaction of numerous influences, including soil physical properties, wheeling, number of passing and farming practices structure of tilled soil layer after wheeling soil water status 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. In intensive agriculture, soil becomes compacted as a consequence of high axle load, damaging the structure of tilled soil and subsoil and reducing crop and soil productivity (Defossez and Richard, 2002) [17]. In coarse-textured soils, axle load exerted pressure in vertical direction. In fine-textured soils, communication would be in multi directional soil (Smith *et al*., 2000) [75]. Possible reason for such variation could be due to variation in the proportion of macropores in different textured soils (Ridge, 2002) [62]. 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. The speed of tractor together with vibration intensity can cause significant effect on soil compaction. 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. 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. 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.

4.2 Effect of striding by animals on soil compaction

Treading through grazing animals may have a significant opposing impact on soil properties and plant development mainly under wet soil conditions. Livestock production is an important part of agriculture world-wide. Ferrero and Lipiec (2000) [81] reported that the frequent grazing and livestock walking produced considerable effects on soil properties and have negative things on soil stability index. The grazing animals also disturb soil aggregates, ensuing in lessening the soil aggregate stability. The soil properties due to the livestock depends on soil kind and soil moisture; (e.g.,) fine-textured soils are more vulnerable to trampling action of grazing animals than coarse-textured soil (Batey, 2009) [6]. Similarly, dry soil faced less trampling act due to high aggregate stability index; however, moist soils are more vulnerable to compaction (Mosaddeghi *et al*., 2000) [49]. Under intensive agriculture, appreciation of dairy farming and livestock rearing exaggerates the deleterious effects of trampling on soil quality, thus outcomes in sizeable decrease in production level and pasture quality (Mitchell and Berry, 2001). Therefore, more pressure motivation is exerted on given soil area under hooves. The level of grazing also sources soil compaction to a diverse extent, more soil compaction with high bulk density was observed in heavy-grazed soil as compared to light-grazed or medium-grazed soils. Besides, soil saturation, root ratio, and soil water infiltration fire also be indictors of examining soil compaction as these soil properties are highly vulnerable to trampling action of animals (Vahhabi *et al*., 2001) [82].

4.3 Effect of raindrop on soil compaction

The direct beating action of raindrop fallen on soil particles by breaking the soil surface. Soil surface became cracks, and fine particle becomes separated from soil clods, which while accompanied with water stagnation settle down to make hard layer of soil thus causing soil compaction. The raindrop when fell on ground transfers its energy to soil particles, and when energy becomes higher than energy-carrying or bearing capacity of soil particles, they (particles) became separated from soil. In rain-fed areas or *kandi* belt, 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 generate natural soil mulch for water conservation in soil. The kinetic energy of the impacting raindrops along with the shearing force of runoff water disperses the soil aggregates and exposes the organic matter. Being concentrated in the surface soil and of low density, soil organic matter is preferentially removed by surface runoff and blowing winds (Lal, 2003) [29]. 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 rainfed or kandi areas, the degree of soil compaction is high because due to high frequency, erratic rainfall, space distribution pattern is not similar. The planker 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. In humid areas are no exact studies will be more imperative.

5. Impact of soil compaction on plants

The soil compaction effects in restricted root growth, declined accessibility of nutrients, enlarged and nutrients loss by leaching, runoff, and gaseous losses to atmosphere which may impacts on plant growth. The soil is sorrow from other types of degradation such as the salinity, drastic belongings of the soil compaction on the plant growth and crop.

5.1 Effect of seedling emergence on soil compaction

The reaction of seedlings improvement to the soil compaction is exposed to soil types and plant species since sometimes modest compaction to the seedlings growth of woody plant species in sandy soils (Alameda and Villar, 2009) [2]. The seedling emergences are unfavourably affected through the soil compaction (Durr and Aubertot, 2000) [21]. The soil compaction is additional damaging to the seedling growth and survival as compared to established plants and trees. In the greenhouse experiment increase in the bulk density from 1.3 to 1.8 g/cm^3 in the late emergence of oak seedlings and a mortality rate of 70% in dry soil (Jordan *et al*., 2003) [32].

5.2 Effect of plant roots on soil compaction

The plants roots play an essential role in the nutrient uptake and plant development and their penetration ability is damagingly affected by the soil compaction due to improved soil strength and reduced number of macropores. The soil compactions on roots generally vary with interspecies and for dissimilar cultivars of the same species, due to difference in root penetration ability depending on the root physiology and morphology. The surface soil compaction is a more limiting factor for the root growth than subsoil compaction (Botta *et al*., 2006) [8]. The impacts of the soil compaction on the ion uptake and root growth are more severe in saline soils than in normal soils. The roots of some cover crops have revealed good penetration ability and less adverse effects of the soil compaction. These crops can be used to alleviate the effects of the soil compaction (Rosolem *et al*., 2002) [65].

5.3 Effect of plant shoots on soil compaction

The rooting association of the plants is rigorously precious through the soil compaction, this does not always consequence in decreased shoot growth could be due to depends on the availability of nutrients in the soil. Uncertainty the soil is so seriously compacted that it reduces the mobility of ions in soil and strictly restricts the root growth. Impact of the soil compaction on plant height but lessening under the yield production (Ishaq *et al*., 2001) [31].

6. Impact of soil compaction on soil biodiversity

The soil compaction can be positive to soil biodiversity and vice versa responsible upon the nature of the soil, climate, and extent of the soil compaction. The soil physical parameters regulate the effect of the soil compaction on physical and chemical properties of the soils and ultimately on soil biota.

6.1 Effect of bacterial population on soil compaction

The soil compaction occasioned in reduced soil aeration of the soil due to 13–36% decreases of air filled porosity which might be due to the lessening in microbial biomass carbon and microbial biomass nitrogen (Tan and Chang, 2007). Soil microbial biomass is undesirably precious through the soil compaction (Pupin *et al*., 2009) [56].

6.2 Effect of enzymatic movement on soil compaction

The soil compaction is changes physico-chemical properties of soil may be due to the reduce of phosphatase, urease, amidase, and dehydrogenase happenings (Tan *et al*., 2008) though sometimes proliferation in the phosphatase activity is also conveyed (Buck *et al*., 2000) [14]. Some disruption or stress to the soil container impact enzymatic activities of soil (Buck *et al*., 2000) [14]. The changes in the microbial communal and favour organisms accomplished of accepting these circumstances, hence, lesser eukaryotic/prokaryotic ratios, more iron and sulphate reducers, and greater methanogens were originate in compacted soils as compared to uncompacted soils (Schnurr-Putz *et al*., 2006) [69].

6.3 Effect of soil fauna on soil compaction

The soil fauna is an important role in the decay and integration of organic matter and home-based is interstitial places in the soil. The soil compaction vagaries the pore size availability and distribution which usually indications to the decrease of the proportion of large pores and affects the movements of nematodes and larger soil fauna. Nematodes, actuality diverse in food habit (bacterivores, herbivores, and omnivores), composition is an important role in the soil food web as well as in organic matter nutrient decomposition and herbivory decomposition (Bouwman and Arts, 2000) [11]. Substantial soil compaction may not affect the quantity of nematodes in the soil but can influence their distribution. (Bouwman and Arts, 2000) [11] informed that the lessening of bacterivore and omnivore nematodes while increase of herbivore nematodes in deeply compacted soils. Earthworms are also described to be influenced by the soil compaction and their population decreases with increase in the soil compaction nevertheless they are capable to penetrate a soil with penetration resistance of 3,000 kPa by ingesting the soil particles (Radford *et al*., 2001) [59].

6.4 Effect of soil flora on soil compaction

The soil flora is real important in the forest ecology in terms of vegetation, productivity, aesthetics, and water and nutrient cycling (Gilliam, 2007). Some disturbance to the forest ecosystem and/or soil affects unfavourably the native ground flora nevertheless particular plant species are capable to illustration healthy habitat and a rapid recovery after extreme degradation of the soil (Demir *et al*., 2008). The soil compaction caused in shifting of ground flora from interior forest species to noxious or invasive and distressed forest species and relative resistance of the initial ground flora to change was found to be linearly related to relative resistance to penetration (Zenner and Berger, 2008). The soil compaction affects the soil biodiversity negatively and it results in reduction in the microbial biomass, enzymatic activity, soil fauna, and ground flora in compacted soils.

7. Remedies to soil compaction evils

The soil compaction is mostly decreased soil porosity and increases soil bulk density. The management of soil compaction, especially in arid and semi-arid regions or *kandi* belt, may be achieved through suitable application of some or all of the following techniques i.e addition of organic matter, controlled traffic, mechanical loosening such as deep ripping, selecting a rotation which includes crops and pasture plants with strong tap roots able to penetrate and break down compacted soils. The land management is better practices are energetic in ensuring that soil physical conditions are not compromised and that practices which intensification the organic content, decrease tillage and sustain utilization of farming systems.

7.1 Soil compaction and organic matter

The organic matter recollects soil water and helping soil to rebound beside compaction. The maintaining an adequate amount of organic matter in the soil stabilizes soil structure and makes it more resistant and reduces bulk density and soil strength (Carter, 2002) [15]. The oxidizable soil organic matter content seems to be more relevant than total organic matter in influential mechanical behaviour of the soil (Ball *et al*., 2000). Another, the less humified the organic matter, the superior is its effect in increasing aggregate porosity and later the greater the decrease in aggregate tensile strength. Since organic materials possess lesser bulk density and superior porosity than that of mineral soils mixing them with soil would improve soil bulk density and porosity (Martin and Stephens, 2001). Though plant residues are a common source of organic matter in the soil and manure is also used extensively by farmers to decline soil compaction and improve soil fertility.

7.2 Managing traffic

The traffic management is a system that relief to maintain a zone more positive for plant growth by restricting soil compaction to the traffic lanes and a loose rooting zone. This proposes that wheel traffic, rather than tillage and cropping, influence be the main factor governing infiltration. The exclusion of wheel traffic in a well-ordered traffic agriculture system, combined with conservation tillage, runs a way to enhance the sustainability of cropping and improved infiltration, raises plant-available water, and reduces soil erosion caused by runoff. Raper *et al*. (1998) [60] reported that the compared the consequence of controlled traffic (total absence of traffic) on soil compaction with trafficked areas and the subsequent effect on crop root penetration on sandy loam (Figure 5). Their outcomes exhibited that soil that was initially completely disrupted to a depth of 51 cm was re-consolidated by traffic into a soil condition comparable to one that had never received a sub-soiling treatment. The energy requirements for different types of tillage are related to tillage depth, soil type, degree of compaction, soil moisture at the time of tilling and to the type of implements to use.

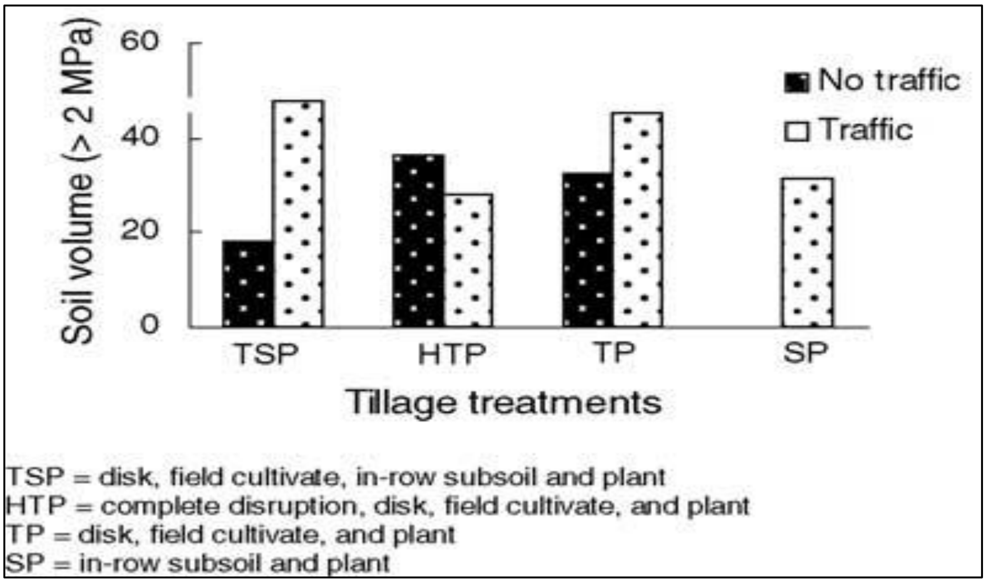

Fig. 5: Effect of tillage and traffic treatment on the proportion of soil volume.

7.3 Soil compaction and deep ripping
The deep cultivation or deep ripping is a significant preparation for eliminating soil compaction, destroying hard pans and ameliorating hard setting of soils. It has become a common management practice used to shatter dense subsurface soil horizons that limit percolation of water and penetration of roots. The subsoil was to improve plant growth has received sporadic care around the world over many years. The increasing soil compaction related with mechanized agriculture and the availability of more powerful tractors and better sub-soilers, ripping can become a favorable soil management exercise. Deep ripping of compacted soil may also improve soil health and ability of plants to resist disease. The growth-stunting disease was eradicated completely, and yields of sultanas (Vitis spp.) enlarged substantially by deep cultivation, which eliminated compacted soil layers (Laker (2001). Though, choosing the true soil moisture and the right combination of ripping depth and tine spacing can lessen the cost of ripping. Ripped soil must be allowed to settle down before seeding, otherwise seeding depth is difficult to regulator and seeds may be placed below the preset seeding depth.

7.4 Soil compaction and plant roots
The hydrostatic pressure (Turgor) inside the elongating area of the root affords the force required to push the root cap and meristematic region through the resisting soil. Uncertainty the hydrostatic pressure is not sufficient to overcome wall resistance and soil impedance, elongation of that particular root tip ceases. The ability of plant roots to penetrate soil is restricted as soil strength increases and ceases entirely at 2.5 kPa. The result of roots on soil structure depends on the types grown, soil constitution and environmental aspects. Plants grown in compacted soil have a smaller number of lateral roots with less dry matter as compared to plants developed under controlled situations at both low and high soil water contents. Soil compaction could be due to adverse effects upon plants growing in the soil by increasing the mechanical impedance to the growth of roots, altering the extent and configuration of the pore space, vexing root diseases such as common root rot of pea by decreasing drainage and thus providing more favor-able soil water surroundings for early infection of pea roots (Allmaras *et al*., 1998). Their response is related to the ability of the root system to overcome the soil strength margins of compacted soil. Plant species that have the ability to penetrate soils with high strength usually possess a deep tap root system.

7.5 Reducing animal trampling
The effect of animal trampling may be reduced if the soil surface is covered with vegetation (Greene *et al*., 1994). The plots with 30% grass cover had the bottommost infiltration rates at all levels of trampling, then 50% cover was satisfactory for maximizing infiltration rates and stopping soil erosion. The two cm canopy height of the forage species shared on hill land pasture was adequate to minimize the special effects of a short-term treading event on soil water infiltration rate and sediment loss in New Zealand (Russell *et al*., 2001) [66]. Silva *et al*. (2000) [71] reported that the animal trampling had no effect on soil physical properties when pasture biomass of oats (Avena spp.) and Italian ryegrass (Lolium spp.) were kept at about 1.0 t ha_1 dry matter.

7.6 Modeling soil compaction
The model is successfully evaluated in field situations for homogeneous soil under a wide range of soil and water circumstances. The measuring of the mechanical processes of compaction in farming soils container provide the necessary understanding to estimate and predict physical changes, allowing comparison with the maximum variations consistent with minimal damage to the productive potential of soil. Several attempts have been made to model soil compaction caused by farm machinery (Defossez and Richard, 2002) [17]. The soil compaction is gotten through wheel traffic treatments most models require a large number of mechanical parameters under incomplete conditions in laboratory bins or in the field with low compaction strengths. Conventionally, stress–strain associations that rely on empirical geo-technical engineering practices have been used to study compaction of agricultural soils. Conversely, these approaches failed to address key features of soil structural dynamics required for modelling of hydraulic properties because they were not adequate for a priori prediction of soil structural changes These models statement soil structural changes induced by internal capillary forces and external steady and transient forces such as passage of a tractor (Or *et al*., 2002) [51]. A model based on Boussinesq Equations has been developed by Defossez and Richard, (2002) [17] which includes: in propagation of the loading forces within the soil resulting from forces applied at the soil surface from farm vehicles, and modelling soil stress-strain behaviour. Their model was modified in order to correct the equations for the plastic properties of soil, and an expression for continuous load distribution and different shapes of the tyre soil interface was obtained by applying the principle of super-position. Nevertheless, we consider that reasonably accurate models that predict soil compaction over a range of conditions may be valuable tools to assist the design of systems fewer damaging to agricultural fabrication.

8. Conclusion
Soil compaction is the worst type of land degradation that limits agricultural productivity and widespread is the current trends, its occurrence is likely to increase. The ever-increasing population of the world requires the intensification of farming systems to manage through the demand for additional food. As a consequence, more and heavier farm machinery and/or animals per land surface area have become common all over the world. This strengthening of the farming system has led to soil compaction and worsening in soil fertility particularly in dryland/rainfed areas. The soil compaction is adversely affects soil fertility, chiefly storage and supply of water and nutrients, through increasing soil bulk density, decreasing porosity and increasing soil strength. These argumentative belongings reduce fertilizer efficiency and crop yield, growth water-logging, runoff and soil erosion with undesirable environmental pollution harms. The practices include minimum (and zero) tillage, minimizing traffic, combining more than one farmhouse operation instantaneously using the same machine to minimize number of passes, minimizing traffic, minimizing intensity of grazing and number of animals per grazing, maintaining vegetative soil cover, loosening compacted soil by deep ripping accompanied and using a rotation which includes deep and strong rooting plants able to penetrate relatively compacted soils. Use of machines with low axle loads and tyres with great surface contact area should be used to minimize ground pressure. Cumulative soil organic matter over stubble retention, green and brown manure or addition of plant or animal organic matter from external sources is also important in decreasing bulk density of the soil and acting as a buffer preventing or lessening the

transmission of compaction to subsoil from external loads acting on the earth. Lastly, farm operations and grazing must be approved out at the minimal suitable soil moisture necessary for farm processes.

9. References

1. Alakkuku L, Weisskopf P, Chamen WCT, Tijink FGJ, Van der Linden JP, Pires S et al. Prevention strategies for field traffic-induced subsoil compaction: a review. Part1. Machine/soil interactions. Soil Tillage and Research. 2003; 73:145-160.
2. Alameda D, Villar R. Moderate soil compaction: implications on growth and architecture in seedlings of 17 woody plant species. Soil Tillage and Research. 2009; 103:325-331.
3. Allmaras RR, Fritz VA, Pfleger FL, Copeland SM. Common root rot of pea (*Pisum sativum* L.): oat pre-crop and traffic compaction effects in fine-textured mollisols. In: Box, J.E. (Ed.), Root Demographics and Their Efficiencies in Sustainable Agriculture, Grasslands and Forest Ecosystems. Proceedings of the 5th Symposium of the International Society of Root Research, 14–18 July, 1996, South Carolina, USA, 1998, 285-294.
4. Ball BC, Campbell DJ, Hunter EA. Soil compactibility in relation to physical and organic properties at 156 sites in UK. Soil Tillage and Research. 2000; 57:83-s91.
5. Ballenger C. The impact of grazing on soil physical properties in a sandy open woodland, Central Australia, Department of Primary Industry and Fisheries Technical Bulletin No. 2001; 289:17.
6. Batey T. Soil compaction and soil management: a review. Soil Use Management. 2009; 25:335-345.
7. Boizard H, Yoon SW, Leonard J, Lheureux S, Cousin I, Roger-Estrade J et al. Using a morphological approach to evaluate the effect of traffic and weather conditions on the structure of a loamy soil in reduced tillage. Soil Tillage and Research. 2013; 127:34-44.
8. Botta G, Jorajuria D, Draghi L. Influence of the axle load, tyre size and configuration, on the compaction of a freshly tilled clayey soil. J Terrra mech. 2002; 39:47-54.
9. Botta G, Jorajuria D, Rosatto H, Ferrero C. Light tractor traffic frequency on soil compaction in the Rolling Pampa region of Argentina. Soil Tillage and Research. 2006; 86:9-14.
10. Botta G, Pozzolo O, Bomben M, Rosatto H, Rivero D, Ressia M et al. Traffic alternatives in harvest of soybean (*Glycine max* L.): effect on yields and soil under direct sowing system. Soil Tillage and Research. 2007; 96:145-154.
11. Bouwman L, Arts W. Effects of soil compaction on the relationships between nematodes, grass production and soil physical properties. Applied Soil Ecology. 2000; 14:213-222.
12. Bouwman LA. Arts WBM. Effects of soil compaction on the relationships between nematodes, grass production and soil physical properties. Applied Soil Ecology. 2000; 14:213-222.
13. Braim MA, Chaney K, Hodgson DR. Effects of simplified cultivation on the growth and yield of spring barley on a sandy loam soil, soil physical properties and root growth; root: shoot relationships, inflow rates of nitrogen; water use. Soil Tillage and Research. 1992 22:173-187.
14. Buck C, Langmaack M, Schrader S. Influence of mulch and soil compaction on earthworm cast properties. Applied Soil Ecology. 2000; 14:223-229.
15. Carter MR. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. Agronomy Journal. 2002; 94:38-47.
16. Cochrane HR, Aylmore LAG. The effects of plant roots on soil structure. In: Proceedings of 3rd Triennial Conference ‘Soils. 1994; 94:207-212.
17. Defossez P, Richard G. Models of soil compaction due to traffic and their evaluation. Soil Tillage and Research. 2002; 67:41–64.
18. Demir M, Makineci E, Gungor B. Plant species recovery on a compacted skid road. *Sensors.* 2008; 8:3123-3133.
19. Dexter AR. Soil physical quality. Effects of soil texture, density, and organic matter, and effects on root growth, part I. Theory. Geoderma. 2004; 120:201-214.
20. Drewry J, Cameron K, Buchan G. Pasture yield and soil physical property responses to soil compaction from treading and grazing-a review. Australian Journal of Soil Research. 2008; 46:237-256.
21. Dbrr C, Aubertot J. Emergence of seedlings of sugar beet (*Betanvulgaris* L.) as affected by the size, roughness and position of aggregates in the seedbed. Plant Soil. 2000; 219:211-220.
22. Fabiola N, Giarola B, da Silva A, Imhoff S, Dexter A. Contribution of natural soil compaction on hardsetting behavior. Geoderma. 2003; 113:95-108.
23. Ferrero A, Lipiec J. Determining the effect of trampling on soils in hill slope woodlands. International Agrophysics. 2000; 14:9-16.
24. Frick J, Degenhardt B, Buchecker M. Predicting local residents’ use of nearby outdoor recreation areas through quality perceptions and recreational expectations. For Snow Landsc Res. 2007; 81:31-41
25. Gilliam F. The ecological significance of the herbaceous layer in temperate forest ecosystems. Bioscience. 2007; 57:845-858.
26. Godwin R, Spoor G, Finney B, Hann M, Davies B. The current status of soil and water management in England. Royal Agricultural Society of England, Stoneleigh, Warwick, 2008.
27. Håkansson I, Lipiec J. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil and Tillage Research. 2000; 53:71-85.
28. Hamza MA, Anderson WK. Improving soil fertility and crop yield on a clay soil in Western Australia. Australian Journal of Soil Research. 2002; 53:615-620.
29. Hamza MA, Anderson WK. Soil compaction in cropping systems. A review of the nature, causes and possible solutions. Soil and Tillage Research. 2005; 82:121-145.
30. Hartemink AE. Soils are back on the global agenda. Soil Use and Management. 2008; 24:327-330.
31. Ishaq M, Hassan A, Saeed M, Ibrahim M, Lal R. Subsoil compaction effects on crops in Punjab. Pakistan I. Soil physical properties and crop yield. Soil and Tillage Research, 2001; 59:57-65
32. Jordan D, Ponder F, Hubbard V. Effects of soil compaction, forest leaf litter and nitrogen fertilizer on two oak species and microbial activity. Applied Soil Ecology. 2003; 23:33-41.
33. Karunatilake UP, Van Es HM. Rainfall and tillage effects on soil structure after alfalfa conversion tomaize on a

clay loam soil in New York. Soil and Tillage Research. 2002; 67:135-146.
34. Keiko N, Tsuyoshi M. Predicting the saturated hydraulic conductivity of compacted sub soils using the non-similar media concept. Soil and Tillage Research. 2005; 84:145-153.
35. Kissling M, Hegetschweiler K, Rusterholz H, Baur B. Shortterm and long-term effects of human trampling on above-ground vegetation, soil density, soil organic matter and soil microbial processes in suburban beech forests. Applied Soil Ecology. 2009; 42:303-314.
36. Koch HJ, Heuer H, Tomanovo O, Murlunder B. Cumulative effect of annually repeated passes of heavy agricultural machinery on soil structural properties and sugar beet yield under two tillage systems. Soil and Tillage Research. 2008; 101:69-77.
37. Kondo MK, Dias Junior MS. Soil compressibility of three latosols as a function of moisture and use. Revista Brasileira de Ciencia do Solo. 1999; 23:211-218.
38. Laker MC. Soil compaction: effects and amelioration. Proceedings of the 75th Annual Congress of the South African Sugar Technologists' Association, Durban, South Africa, 2001, 125-128.
39. Lal R. Soil erosion and the global carbon budget. Environmental and International. 2003; 29:437-50.
40. Li YuXia, Tullberg JN, Freebairn DM. Traffic and residue cover effects on infiltration. Australian Journal of Soil Research. 2001; 39:239-247.
41. Lipiec J, Ferrero A, Giovanetti V, Nosalewicz A, Turski M. Response of structure to simulated trampling of woodland soil. Adv Geoecol. 2002; 35:133-140.
42. Lipiec J, Hatano R, Slowin˜ska-Jurkiewicz A. The fractal dimension of pore distribution patterns in variously-compacted soil. Soil and Tillage Research. 1998; 47:61-66.
43. Mapa B, Green RE, Santo L. Temporal variability of soil hydraulic properties with wetting and drying subsequent to tillage. Soil Science Society of America Journal, 1986; 50:1133-1138.
44. Martin PJ, Stephens W. The potential for biomass produc-tion on restored landfill caps. In: Bullard, M.J., Christian, D.G., Knight, J.D., Lainsbury, M.A., Parker, S.R. (Eds.), Aspects of Applied Biology. 2001; 65:337-344.
45. Matthews GP, Laudone GM, Gregory AS, Bird NRA, Matthews AG, Whalley WR. Measurement and simulation of the effect of compaction on the pore structure and saturated hydraulic conductivity of grassland and arable soil. Water Resources Research. 2010; 46:5.
46. Medvedev VV, Cybulko WG. Soil criteria for assessing the max-imum permissible ground pressure of agricultural vehicles on Chernozem soils. Soil and Tillage Research. 1995; 36:153-164.
47. Mitchell FJ, Berry WAJ. The effects and management of compaction in agricultural soils. Proceedings of the Annual Congress— South African Sugar Technologists Association No. 2001; 75:118-124.
48. Montagu KD, Conroy JP, Atwell BJ. The position of localized soil compaction determines root and subsequent shoot growth responses. Journal of Experimental Botany. 2001; 364:2127-2133.
49. Mosaddeghi MR, Hajabbasi MA, Hemmat A, Afyuni M. Soil compactibility as affected by soil moisture content and farmyard manure in central Iran. Soil and Tillage Research. 2000; 55:87-97.
50. Ohu JO, Folorunso OA, Aeiniji FA, Raghavan GSV. Critical mois-ture content as an index of compactibility of agricultural soils in Bormo state of Nigeria. Soil Technology. 1989; 2:211-219.
51. Or D, Ghezzehei T.A. Modeling post-tillage soil structural dynamics: a review. Soil and Tillage Research. 2002; 64:41-59.
52. Pagliai M, Marsili A, Servadio P, Vignozzi N, Pellegrini S. Changes in some physical properties of a clay soil in Central Italy following the passage of rubber tracked and wheeled tractors of medium power. Soil and Tillage Research. 2003; 73:119-129.
53. Pagliai M, Vignozzi N. The soil pore system as an indicator of soil quality. Advances in Geo Ecology. 2002; 35:69-80.
54. Panayiotopoulos KP, Papadopoulou CP, Hatjiioannidou A. Compaction and penetration resistance of an Alfisol and Entisol and their influence on root growth of maize seed-lings. Soil and Tillage Research. 1994; 31:323-337.
55. Piñeiro G, Paruelo J, Oesterheld M, Jobbágy E. Pathways of grazing effects on soil organic carbon and nitrogen. Rangeland Ecology and Management. 2010; 63:109-119.
56. Pupin B, Freddi O, Nahas E. Microbial alterations of the soil influenced by induced compaction. Rev Bras Cienc Solo. 2009; 33:1207-1213.
57. Quiroga AR, Buschiazzo DE, Peinemann N. Soil compaction is related to management practices in the semi-arid Argentine pampas. Soil and Tillage Research. 1999; 52:21-28.
58. Radford B, Bridge B, Davis R, Mc Garry D, Pillai U, Rickman J, Walsh P, and Yule D. Changes in the properties of a Vertisol and responses of wheat after compaction with harvester traffic. Soil and Tillage Research. 2000; 54:155-170.
59. Radford B, Wilson-Rummenie A, Simpson G, Bell K. Ferguson M. Compacted soil affects soil macrofauna populations in a semi-arid environment in central Queensland. Soil Biology and Biochemistry. 2001; 33:1869-1872.
60. Raper RL, Reeves DW, Burt EC. Using in-row subsoil-ing to minimize soil compaction caused by traffic. Journal of Cotton Science. 1998; 2:130-135.
61. Ressia JM, Mendivil G, Balbuena RH, Chidichimo O. Root growth and grain yield of corn in relation to tillage systems. In Proceedings of the IV CADIR Argentine Congress on Agricultural. 1998.
62. Ridge R. Trends in sugar cane mechanization. Int. Sugar J. 2002; 104:164-166.
63. Riethmuller GP, Jarvis RJ. The effect of tine spacing and tillage depth on a subsoilers energy requirements on a deep yellow loamy sand. Conference on Agricultural Engineering, Adelaide, 1986, 315-319.
64. Rosolem C, Foloni J, Tiritan C. Root growth and nutrient accumulation in cover crops as affected by soil compaction. Soil and Tillage Research. 2002; 65:109-115.
65. Rosolem CA, Foloni JSS, Tiritan CS. Root growth and nutrient accumulation in cover crops as affected by soil compaction. Soil and Tillage Research. 2002; 65:109-115.
66. Russell JR, Betteridge K, Costall DA, Mackay AD. Cattle treading effects on sediment loss and water

infiltration. Journal of Range and Management. 2001; 54:184-190.
67. Sakai H, Nordfjell T, Suadicani K, Talbot B, Bøllehuus E. Soil compaction on forest soils from different kinds of tires and tracks and possibility of accurate estimate. Croat J For Eng. 2008; 29:15-27.
68. Sarah P, Zhevelev H. Effect of visitors' pressure on soil and vegetation in several different micro-environments in urban parks in Tel Aviv. Landscape Urban Plan. 2007; 83:284-293.
69. Schnurr-Putz S, Guggenberger G, Kusell K. Compaction of forest soil by logging machinery favours occurrence of prokaryotes. FEMS Microbiol Ecol. 2006; 58:503-516.
70. Sigua GC, Coleman SW. Long-term effect of cow congregation zone on soil penetrometer resistance: implications for soils and forage quality. Agronomy and Sustainable Development. 2009; 29:517-523.
71. Silva AP, Imhoff S, Corsi M. Evaluation of soil compaction in an irrigated short-duration grazing system. Soil and Tillage Research. 2003; 70:83-90.
72. Silva VR, Reinert DJ, Reichert JM. Soil strength as affected by combine wheel traffic and two soil tillage systems. Ciencia Rural. 2000; 30:795-801.
73. Silveira M, Comerford N, Reddy K, Prenger J, DeBusk W. Influence of military land uses on soil carbon dynamics in forest ecosystems of Georgia, USA. Ecology Indic. 2010; 10:905-909.
74. Sinnett D, Morgan G, Williams M, Hutchings T. Soil penetration resistance and tree root development. Soil Use and Management. 2008; 24:273-280.
75. Smith R, Pröschle T. Effect of moisture and transit frequency on stress distribution on different soils. Agro Sur. 2000 28:60-68.
76. Sowa J, Kulak D. Probability of occurrence of soil disturbances during timber harvesting. Croat J For Eng. 2008; 29:29-39.
77. Stalham MA, Allen EJ, Herry FX. Effects of soil com-paction on potato growth and its removal by cultivation. Research review British Potato Council, Oxford, UK, 2005.
78. Tan X, Chang S. Soil compaction and forest litter amendment affect carbon and net nitrogen mineralization in a boreal forest soil. Soil and Tillage Research. 2007; 93:77-86.
79. Tan X, Chang S, Kabzems R. Soil compaction and forest floor removal reduced microbial biomass and enzyme activities in a boreal aspen forest soil. Biology and Fertility of Soils. 2008; 44:471-479.
80. Unger PW, Kaspar TC. Soil compaction and root growth: a review. Agronomy Journal. 1994; 85:759-766.
81. Usowicz B, Lipiec J. Spatial distribution of soil penetration resistance as affected by soil compaction: the fractal approach. Ecology Complex. 2009; 6:263-271.
82. Vahhabi MR, Rahimzadegan R, Bassiri M. Determining and comparing infiltration characteristics in clay soils in grazed vs. nongrazed range sites in Fereydan Region of Isfahan. Iranian J Nat Resour. 2001; 54:75-91.
83. Van den Akker, JHH, Arvidsson J, Horn R. Introduc-tion to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. Soil and Tillage Research. 2003; 73:1-8.
84. Vitlox O, Loyen S. Consequences de la mecanisation sur la com-paction du sol *et al*. linfiltration de leau. Compte rendu de la journal ditude: Erosion hydrique et coulies boueuses en Region Wallonne, 2002, 45-58.
85. Webb R. Recovery of severely compacted soils in the Mojave Desert, California, USA. Arid Land Research Management. 2002; 16:291-305.
86. Wiermann C, Werner D, Horn R, Rostek J, Werner B. Stress/strain processes in a structured unsaturated silty loam Luvisol under different tillage treatment in Germany. Soil Tillage Res. 2000; 53:117-128.
87. Williamson J, Neilsen W. The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting. Candian Journal of Forest Research. 2000; 30:1196-1205.
88. Wortmann CS, Jasa PJ. Management to minimize and reduce soil compaction. Cooperative Extension, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 2003.
89. Yavuzcan HG. Wheel traffic impact on soil conditions as influenced by tillage systemin central Anatolia. Soil and Tillage Research. 2000; 54:129-138.
90. Yu H, Mitchell J. Analysis of cone resistance: review ofmethods. Journal of Geotechnology and Geoenvironmental. 1998; 124:140-148
91. Zenner E, Berger A. Influence of skidder traffic and canopy removal intensities on the ground flora in a clearcut-with-reserves northern hardwood stand in Minnesota, USA. Forest Ecology and Management. 2008; 256:1785-1794.