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Influence of Agricultural Machinery Traffic on Soil Compaction Patterns, Root Development, and Plant Growth, Overview

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Abstract: Healthy cropping system, which delivers production, environmental and efficiency benefits to those who implement it. It literally means to control where you drive during cropping operations by driving along clearly defined, permanent wheel tracks, with the aim of minimizing the area affected by wheeled compaction. By doing this we separate our paddocks into sections, one which provides a healthy well structured medium for supporting crop growth, and one which provides the roadways for supporting vehicles and machinery. Raised bed farmers do all those things as part of their bed and furrow system. Current cropping practices produce a cycle between soil compaction produced by off-road equipment and the alleviation of this condition by means of tillage or natural processes such as freezing and thawing. The adverse effects of soil compaction on crop growth have been recognized for years. Bulk density and soil strength are two physical properties which quantify soil compaction.

Key words: Machine effects · management systems · plant roots · soil physical properties · soil compaction · tillage systems · soil compaction · soil and water contents · machinery traffic

INTRODUCTION

Healthy cropping system, which delivers production, environmental and efficiency benefits to those who implement it. It literally means to control where you drive during cropping operations by driving along clearly defined, permanent wheel tracks, with the aim of minimizing the area affected by wheeled compaction. By doing this we separate our paddocks into sections, one which provides a healthy well structured medium for supporting crop growth, and one which provides the roadways for supporting vehicles and machinery. Raised bed farmers do all those things as part of their bed and furrow system. Current cropping practices produce a cycle between soil compaction produced by off-road equipment and the alleviation of this condition by means of tillage or natural processes such as freezing and thawing. The adverse effects of soil compaction on crop growth have been recognized for years. Bulk density and soil strength are two physical properties which quantify soil compaction.

Buader [1] investigated the effect of four continuous tillage systems on mechanical impedance of clay loam soil. They reported that increases in bulk density are correlated with increases in penetration resistance.

Veihmeyer and Hendrickson [2] reported that soil compaction reduces root growth. Such soil conditions can decrease crop yields, a result which is certainly undesirable to farmers. Farmers want to be productive by enhancing plant growth and maximizing yields, Phillips and Kirkham [3] and Morris [4] reported corn yield reductions of 10 to 22 percent due to compaction. For each 1 kg m^{-3} increase in bulk density, a decrease in maize grain yields of 18% relative to the yield on a noncompacted plot [5]. Increased soil compaction can reduce yields in potatoes of up to 22 percent [6] and decrease wheat growth [7]. These results illustrate the potential for compaction to depress crop yields. Extremely dense soil impedes root growth and thereby limits water consumption of plants. Thus, soil compaction must be managed in order to keep its detrimental effects to a minimum.

The level of compaction which requires tillage for a given soil type is not well understood. No generally accepted rule of thumb exists which states that a certain bulk density or penetrometer strength limits plant

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productivity. However, some studies have been conducted which address these two parameters in predicting detrimental effects to plant growth.

Bowen [8] Suggested a general rule (with many exceptions) that bulk density measurements of 1.55, 1.65, 1.80 and 1.85 mg m^{-3} can impede root growth and thus will reduce crop yields on clay loams, silt loams, fine sandy loams, and loamy fine sands, respectively. Bulk density greater than 1.2 mg m^{-3} for clay soil, 1.6 mg m^{-3} for loam soil, and 1.8 mg m^{-3} for sandy loam adversely affected the root growth of rice [9].

Proposed a bulk density less than or equal to 1.3 mg m^{-3} in any soil as non-limiting to crop growth [10]. However, Singh *et al.* [10] stated that due to the lack of research literature, the maximum value of bulk density which may be considered unusable by plants is 2.1 mg m^{-3} in any type of soil.

Soil strength is an indicator of how easily roots can penetrate soil. Cone index is a measure of soil strength and is measured using a penetrometer. The magnitude of mechanical impedance to root penetration which decreases plant growth is also unknown. Ehlers [11] stated that the penetrometer resistance limiting to oats was 3.6 MPa in tilled Ap horizon, but 4.6 to 5.1 MPa in the untilled Ap horizon and in the subsoil. The limiting penetrometer resistance depends upon the soil conditions and characteristics and the crop of interest.

Ayers and Perumpral [12] pointed out that dry density had a considerable influence on cone index at low moisture contents for soils containing a certain percentage of clay. Cone index became less dependent on dry density at higher moisture contents.

Sojka [13] studied the effect of penetrometer resistance on sunflowers. A soil strength corresponding to a penetrometer resistance of 2 MPa produces some root restriction and a resistance of 3 MPa creates a total barrier to root elongation. A maximum root growth pressure for citrus is 1.5 Mpa.

Murdock *et al.* [14] suggested a penetrometer reading of 2.07 MPa (300 psi) as indicative of severe compaction for Kentucky soils. A penetrometer measurement of 2.0 MPa generally regarded as sufficient to hinder the growth and development of crops. However, precise cone index levels which limit plant growth for specific soil types have been rarely documented.

The development of precision farming has risen from the recent interest in increasing productivity of land [15]. Site-specific farming utilizes GPS and GIS systems connected to automatic controllers which regulate field inputs. Future research and development may make site-specific control applications economically viable in agricultural production. As technology advances, the cost of GPS/GIS systems will decrease and the feasibly of such systems to farmers will increase. These systems may also perform multiple tasks such as controlling the inputs of planters and sprayers, allowing the sharing of equipment costs between different applications. Thus, farmers can use one controller for various applications. Inputs can usually be decreased by varying the rate of application to meet requirements which vary spatially over fields and therefore save farmers money.

Lal *et al.* [16] successfully demonstrated that GIS can be combined with site-specific models for regional planning and productivity analysis.

Luo and Wells [17] described a dual-probe density gauge in detail and its use in field investigations. Gamma ray attenuation measures the soil bulk density between the two probes while neutron thermalization is used for measuring water content. Various depths between 5.1 cm and 91.4 cm can be selected in 5.1 cm increments. Vertical access holes (2.54 cm in diameter and 30.5 cm apart) for the dual probe gauge were made using a tractor mounted, hydraulically operated device. One probe contains the gamma and neutron sources while the other probe contains the detector for counting the gamma rays and each must be set at the same depth during a test.

The total volume of a soil aggregate is made up of soil grains and pore spaces.

Hillel [18] reported that an “ideal soil”, by volume, contains about 50% solid particles and about 50% pore space, and the bulk density of this kind of mineral soil is approximately 1.3 mg m^{-3}. The particle density of a soil is 2.65 mg m^{-3} for all practical calculations [19].

Logsdon *et al.* [20] studied the persistence of subsoil compaction from heavy axle load. They reported that subsoil density increased while the infiltration was reduced because heavy axle load on the soil surface resulted in compaction that persisted despite of freeze/thaw and wetting/drying cycles.

Taylor [21] examined the effects of total axle load on subsurface soil compaction using two different tire sizes, and adjusted the total load to give equal pressures at the soil-tire interface. They reported that larger tire always produced greater soil pressure at all depths.

Lyasko and Terzian [22] in their study, to evaluate compaction and directional stability of wheeled tractors operating on hillsides, found that compaction depends on tractor and wheel design, wheel track width, working load and land slope. They further reported that compaction reduces with increase of land slope and greatest soil compaction occurs under the wheel rut on level ground.

Abebe *et al.* [23] studied the effect of load and multiple passes on soil compaction. They concluded that the surface and the subsurface soil deformation characteristics, which were taken as indicative values of soil compactibility, strongly indicated that the maximum compaction occurred during the first three passes of a loaded wheel, Jonhson *et al.* [24] using dimensional analysis, developed a model to predict soil compaction in clay soil. They considered the effect of cone index, soil moisture, axle load, tire parameters and number of tire passes on compaction. They concluded that soil compaction caused by agricultural vehicle traffic can be predicted.

Soil compaction is a real problem in agriculture and therefore must be properly managed and remedied. Jonhson *et al.* [25] reported that, in future, soil compaction research should be directed to predict forces produced by machines affecting soil compaction, propagation of compaction forces (stress propagation) in the soil as a function of soil properties and loading characteristics, soil response to compaction, specify limits of compactness for efficient traction and mobility of vehicles, specify limits of compactness for optimum plant growth, and develop management systems that include the management of compactness for all aspects of crop production. Considering the threats that soil compaction imposes to crop production, it is therefore necessary to develop measures by appropriate management of the available soil, tire and external variables in order to minimize the detrimental effect of soil compaction. Thus, this study was geared to develop soil compaction models to facilitate solutions to site-specific soil compaction problems.

Farming under compaction: Intensive farming of crops and animals has spread all over the world and involves shorter crop rotations and heavier machinery that lead to an increase in soil compaction [26]. The extent of compacted soil is estimated worldwide at 68 million hectares of land from vehicular traffic alone [27]. Soil compaction is estimated to be responsible for the degradation of an area of 33 million ha in Europe [28] and about 30% (about 4 million ha) of the wheat belt in Western Australia [29]. Similar problems related to soil compaction have been reported in almost every continent (Australia; Azerbaijan; Japan; Russia; France; China; Ethiopia [30-37].

Although farming systems have improved significantly to cope with the new pressures associated with intensive agriculture, the structure of many otherwise healthy soils has deteriorated to the extent that crop yields have been reduced. Soil compaction is defined 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” [38] and is related to soil aggregates because it alters the spatial arrangement, size and shape of clods and aggregates and consequently the pore spaces both inside and between these units [39].

The nature and extent of this degradation, which can be exaggerated by the lack of organic matter, has been recognised worldwide. Compaction also affects the mineralization of soil organic carbon and nitrogen [40] as well as the concentration of carbon dioxide in the soil [41].

Although compaction is regarded as the most serious environmental problem caused by conventional agriculture [42], it is the most difficult type of degradation to locate and rationalize, principally as it may show no evident marks on the soil surface. Unlike erosion and salting that give strong surface evidence of the presence of land degradation, degradation of soil structure requires physical monitoring and examination before it is uncovered and its extent, nature and cause resolved. The hidden nature of soil structural degradation (SSD) leads to specific problems such as poor crop growth or water infiltration that may be blamed on other causes. In addition, SSD is often blamed for poor crop performance when it is actually not present. Farmers rarely link their land management practices to the causes of SSD and remain unaware that many deep-ripping exercises worsen SSD [43]. Because subsoil compaction is very persistent and possibilities of natural or artificial loosening have been disappointing, it has been acknowledged by the European Union (EU) as a serious form of soil degradation [44].

The effects of soil compaction on crops and soil properties are complex [45] and since the state of compactness is an important soil structural attribute, there is a need to find a parameter for its characterization, such as relative bulk density, that gives directly comparable values for all soils [46]. 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 characterise the state of soil compactness [47]. However, in swelling/shrinking soils the bulk density should be determined at standardised moisture contents, to prevent problems caused by water content variations [46].

Soil strength is also used as a measure of soil compaction because it reflects soil resistance to root penetration [48-52]. 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 [52, 53].

Interestingly a slight degree of topsoil compaction may prove beneficial for some soil types [54] indicating that there is an optimum level of compaction for crop growth. The concept of optimum level of compaction is important, especially in controlled traffic system where any external source of compaction is avoided because it might cause a sub-optimal level of compaction and yield depressions. Also if compaction is confined to the sub-surface only, roots may grow more laterally or coil upward toward the less compacted layers with no significant decrease in yield [55].

This review concentrates mainly, though not exclusively, on crop/livestock systems in the rainfed areas. It mainly considers research published in the period since the major reviews on soil compaction by [56, 57].

Factors effecting soil compaction: In modern agriculture, farm animals and machines cause most of the soil compaction. Working the soil at the wrong soil water content exacerbates the compaction process. Accordingly, the influence of soil water content and compaction induced by farm animals and machines will be reviewed here.

Influence of soil water content on soil compaction: Sonae and Van Ouwerkerk [58] reported that soil water content is the most important factor influencing soil compaction processes. At all compaction levels, the penetration resistance increases with decreasing soil water potential [59]. In other words, increasing soil moisture content causes a reduction in the load support capacity of the soil [60], thus decreasing the permissible ground pressure [61]. Knowing the changes in soil compaction with changes in water content helps to schedule farm trafficking and cultivation operations at the appropriate moisture content.

Ohu [62] Investigated that soil deformation increases with moisture content and the number of passes [63] and timing of tillage in relation to soil water moisture content and soil texture [64]. Accordingly it is important to till the soil at the right soil moisture if compaction is to be minimized.

Gysi [65] Reported that moist soil responded at a depth of 12-17 cm to a ground contact pressure of 160 kPa with an increase in bulk density and consolidation pressure, as well as with a decrease in air permeability and macro-porosity. With ground contact pressure of 130 kPa, however, only slight changes of the soil structure were detected at a depth of 32-37 and 52-57 cm and the measurements did not indicate any compaction.

In soils with low moisture however, ‘simplified’ tillage had no influence on soil density to 30 cm depth [66].

Quiroga [67] Compare that soil compaction and soil moisture are only significant when comparing soils of the same depth because considerable variation between depths in the same profile, and between profiles, makes it difficult to compare results. For any compaction energy level it is thus necessary to define the moisture content of the soil corresponding to the liquid, plastic and solid limits. These limits are dependent on the clay content and its mineralogical characteristics. Soil moisture lower than PL is desirable for cultivation [68] and the most appropriate soil moisture content is 0.95 PL [69]. At high soil moisture, the difference in soil resistance between compacted soil (with traffic) and un-compacted soil (no traffic) is low and usually smaller than the value that limits root growth (>2 MPa). However, as soils get drier, soil compaction in the topsoil becomes observable.

Low soil water content, even maximum loads did not deform the soil more than 2 cm in depth while at higher soil water content the value of the permissible load (the load which causes no significant soil compaction) was appreciably lower. This means that the maximum permissible ground pressure of agricultural vehicles to permit satisfactory crop production decreases with decreasing soil bulk density and increasing soil moisture. For a given external load, soil compaction increases with increasing moisture. When traffic frequency decreases, the compaction factor diminishes and this decrease is more gradual in a wet soil than in a dry one. However, increasing soil compaction with increasing soil moisture is valid up to a certain value called the optimum moisture content, above which increasing soil moisture content results in decreases in compaction under a given load as the soil becomes increasingly plastic and incompressible [61, 70].

Mechanized farm operations and soil compaction: Tullberg [71] investigated that trafficking by wheeled farm machines is common in most agricultural operations even in zero tillage systems. Tilling, harvesting and spreading of chemicals or fertilisers are the common operations in most farms. Most, if not all these operations are performed by heavy, wheeled machines. Soil compaction by wheels is characterised by a decrease in soil porosity localised in the zone beneath the wheel and rut formation at the soil surface.

The degree of compaction depends on the following: soil mechanical strength, which is influenced by intrinsic soil properties such as texture and soil organic matter contents [72, 73]; structure of the tilled layer at wheeling [74] and its water status [75]; and loading, which depends on axle load, tyre dimensions and velocity, as well as soil-tyre interaction [76].

It has been estimated that over 30% of ground area is trafficked by the tyres of heavy machinery even in genuine zero tillage systems (one pass at sowing) [71]. Under minimum tillage (2-3 passes) the percentage is likely to exceed 60% and in conventional tillage (multiple passes) it would exceed 100% during one cropping cycle. Soane *et al.*, [56] showed that tillage and traffic using heavy machines can also induce subsoil compaction in different soil types and climatic conditions in cropped systems [77, 78]. Discuss that the depth of the compaction varies widely from 10 to 60 cm [79] but it is more obvious on topsoil (around 10 cm).

Balbuena [80] Study that the cone index (penetrometer reading) increments of between 16 and 76% can occur in the first 40 cm of the surface layer, and bulk density can also increase but increases were limited to a 15 cm depth in a study by . However, in a grassland situation differences between heavy and light loads in the shallower depth range (topsoil) were not found [81].

The long-term effect of reduced tillage on soil strength properties was studied by Wiermann ***et al.*** [82] on a silty loam soil in Germany. The repeated deep impact of tillage tools in conventionally treated plots (CT) resulted in a permanent destruction of newly formed soil aggregates. This led to a relatively weak soil structure of the tilled horizons as dynamic loads as low as 2.5 t induced structural degradation. In the conservation tillage (CS) plots, in contrast, a single wheeling event with 2.5 t was compensated by a robust aggregate system and did not lead to structural degradation. Thus higher soil strength due to the robust aggregate system was provided by reduced tillage. Increasing wheel loads and repeated passes resulted in increasing structural degradation of the subsoil in both tillage systems.

Benito [83] Investigate that the effects of traditional tillage, minimum tillage, and no-tillage on soil water, soil organic matter and soil compaction, they found that the no-tillage treatment conserved much more soil water than traditional tillage and minimum tillage treatments, especially in dry years. Soil compaction was less in traditional tillage, but there was more compaction in the subsoil after harvesting, thus resulting in less soil compaction than in the no-tillage treatment. The level of soil organic matter increased after minimum tillage and no-tillage treatments. However, some workers prefer minimum or conventional tillage over no-tillage, saying that it may provide more favorable soil physical conditions for the growth of the crop when compared to no-tillage.

Tormena [84] Reported that the critical values beyond which root penetration is severely restricted (>2 MPa) were mainly observed for the no-tillage system [85]. On any surface where wheels are operated tillage is required to return the soil to low impedance for root exploration and to a conductive state for water infiltration.

Carter [86] suggested that if farm operations are performed when soil is dry to very dry, soil compaction could be minimised significantly. Random traffic can severely compact the soil, reduce infiltration, and increase energy consumption.

Li HongWen [87] reported that however, tillage is required under any surface where wheels are operated to return the soil to low impedance for root exploration and to a conductive state for water infiltration. Soil managed with no traffic or tillage during seedbed preparation is stable, with lower soil impedance and higher water infiltration than soil in tilled and trafficked plots. Adoption of these findings will also reduce unit production costs [86].

Axle load as a source of soil compaction: The differences between force and pressure when dealing with compaction caused by farm animals or machines should be clearly distinguished. Axle load is the weight of the farm animal or machine in kg or kN, which is a unit of force, while ground contact pressure is the axle load divided by the surface area of contact between the animal or machine and soil. This is measured in kPa, which is a unit of pressure. The ground contact pressure is what causes soil compaction.

Most of the soil compaction in intensive agriculture is caused by external load on soil from farm machinery or livestock [39]. This causes considerable damage to the structure of the tilled soil and the subsoil, and consequently to crop production, soil workability and the environment. The over-compacted soils are generally found along the wheel tracks and on the turning strips at field edges [88] with the effects more marked on topsoil [89]. There is evidence that topsoil compaction is related to ground pressure while subsoil compaction is related to total axle load independently of ground pressure.

Severe structural degradation caused by agricultural machinery restricts or impedes plant growth and thus should be limited to layers that can be structurally reclaimed and re-molded with reasonable effort by tillage. Almost all models of tractors and machines generate pressures above the limits recommended as maximum to avoid soil compaction [90-92]. It is suggested that the most effective means of protecting soil from structure degradation by the action of agricultural machines is to use units that carry out several operations simultaneously. This will lead to a significant reduction in the number of wheel passes [31].

Radford [93] determined the changes in various soil properties immediately after the application of a known compaction load (10 and 2 Mg load on the front and rear axles, respectively) to a wet Vertisol and found that compaction was mostly restricted to the top 20 cm of the soil where it decreases the number of pores per unit area in each of the three size ranges at both zero (soil surface) and 10 cm depth, soil type also influences soil compaction.

Soil with coarse texture, the dominant penetration of stress was in the vertical direction, while in soil with a finer texture stress propagation was multidirectional. However, they suggested that in soil with a good structure (aggregated soil) compaction due to axle load was not as deep. The effects of axle loads on soil compaction have been researched by many workers all over the world in the last decade [94-98].

Effects of wheels and tyres on soil compaction: Horn *et al.* [99] and Blaszkiewicz [100] study the wheel load, tyre type and inflation pressure increase soil bulk density and play an important role in soil compaction. Almost all tyres significantly increase soil compaction in the wheel track, while only some of them increase soil compaction near the track. At greater distances from the wheel track, a general reduction in soil compaction occurs, especially in the subsoil. Soil compaction due to wheeling has been shown to result in higher bulk density values in contrast to soil shearing, which either maintained or increased the pore volume.

Many workers have reported that operating with low-pressure tyres can significantly decrease soil compaction and increase crop yield while high tyre inflation pressure increases soil compaction [56, 98, 101]. On the other hand, tyre ground pressure values vary significantly between different machines with trailers, slurry tankers and combine harvesters exerting the highest ground pressures [102, 103]. However, ground pressures exerted by tyres are strongly reduced by a sand layer at the surface and it has been suggested that it is better to use a non-homogeneous load distribution for predicting soil compaction under tyres of agricultural machinery. It also has been suggested that floatation tyres appeared to be the preferred option with respect to several key parameters (fuel consumption, drawbar draught, wheel rut depth, dry bulk density) under particular soil and loading conditions [104]. Reduced ground contact pressure systems in which vehicles, machines and implements are fitted with tracks or larger than standard tyres with low inflation pressures (such as radial tyres) are suggested to increase tractive efficiency and reduce tyre/soil contact pressure and, thereby, the potential for compaction.

Wider wheels fitted with radial tyres to reduce soil compaction are generally preferred to those with metal tracks and diagonal-ply tyres which usually destroy the structure of arable layers more than radial tyres. They also suggested that tractors with rubber tracks led to greater compaction of the topsoil but the more damaging compaction of the subsoil was less [92, 105-107].

The influences of wheel and tracked machines on soil compaction were compared who reported that although the wheeled machine caused deeper ruts than the tracked one, alterations caused by the two machines to the measured soil parameters (dry bulk density, penetration resistance, intrinsic air permeability, saturated hydraulic conductivity, porosity and pore-size distribution) were similar, except in the uppermost 5-10 cm. The wheeled machine caused a decrease in bulk density, whereas the tracked machine caused an increase, despite its lower ground pressure [108]. Tyre pressure also influences wheel load such that heavier loads can be used with low tyre pressures before deformation occurs [95]. Overall, in considering the benefits of decreasing ground pressure and increasing ground contact area it is important to recognise that the total area of the field trafficked by such wheels is greater than is the case with narrow wheels using high pressure. This can mean that there is actually more compaction of the topsoil over a whole field with low ground pressure in the tyres than with high ground pressure but the damage to the soil is likely to be greater with the narrower tyres at higher pressures.

Wheel slip also influences degree of soil compaction. For example, reported that slip influenced degree of soil compaction to a depth of 5 cm and a 30% level of slip produced significant differences in degree of soil compaction. Although there was an increasing compaction effect from 19.2 to 31.9% slip, no significant differences were observed among the cone index values for the 10-20% slip. However, improving traction characteristics with the use of radial tyres can reduce wheel slip and increase forward speed significantly [106, 109].

Number of passes: Intensity of trafficking (number of passes) plays an important role in soil compaction because deformations can increase with the number of passes [63, 110]. Experimental findings have shown that all soil parameters become less favorable after the passage of a tractor and that a number of passes on the same tramlines of a light tractor, can do as much or even greater damage than a heavier tractor with fewer passes. The critical number of passes was ten, beyond which advantages from the use of a light tractor were lost [111].

However, the first pass of a wheel is known to cause a major portion of the total soil compaction. Subsoil compaction may be induced by repeated traffic with low axle load and the effects can persist for a very long time [63, 89]. Wheeled traffic from machinery with axle load in excess of 9 mg can cause increases in bulk density and penetrometer resistance in subsoil at a depth >30 cm below the surface. These changes in physical properties can lead to long-term yield suppression. In highly weathered soils, compaction may not increase the strength but may reduce the porosity, thus restricting water supply to the root surface [112].

Alakukku [96] reported that in both clay (Vertic Cambisol) and organic soil (Mollic Gleysol), the penetrometer resistance was 22-26% greater, the soil water contents were lower, and the soil structure more massive, in plots compacted with four passes than in the control plots.

These data were supported by Siker and Isildar [113] who reported that the number of tractor passes increased soil bulk density and compaction, and decreased total porosity, void ratio, air porosity and drainage porosity. These findings were also supported by Balbuena *et al.* [89] who reported that 10 passes significantly affected soil properties of the surface layer to 50 cm depth compared to the 1-pass and no-traffic control treatments.

Trampling and soil compaction: Treading by grazing animals can have a significant adverse effect on soil properties and plant growth, particularly under wet soil conditions [114-116]. It may also affect water and nutrient movement over and through soil. Soil compaction due to animal trampling is one of the factors responsible for the degradation of the physical quality of soils and mainly influences soil parameters such as soil structure [117].

The intensification of dairy farming has also been found to have a deleterious effect on soil quality, particularly in terms of compaction by trampling, which results in losses of production, pasture quality and hydraulic conductivity [118]. One of the most important soil properties vulnerable to animal trampling is penetration resistance, which is highly sensitive to animal trampling.

Linked the critical values of penetration resistance for grazing to the depth of water table and weight of animal [119]. They reported that the limits of penetration resistance without any trampling damage to the grass were 600 and 800 kPa, depending on the weight of cattle (300-500 kg per head). They also found that with homogeneous conditions of soil and vegetation, the critical value of penetration resistance (800 kPa) corresponded to a groundwater level of 30 cm below the soil surface. With heterogeneous soil and vegetation, the critical value (600 kPa) was, in wet periods, at a groundwater level of 20-60 cm and in dry periods was at 0-30 cm, depending on the dominant plant species.

Mapfumo [120] reported that surface (0-2.5 cm) bulk density and penetration resistance was significantly greater under heavily grazed than under medium and lightly grazed meadow. Trampling can also significantly influence soil saturation capacity and root ratio [121] and reduces soil water infiltration.

Soil compaction induced by trampling is affected by the following: [122, 123], (a) trampling intensity [123, 124]; (b) soil moisture [125]; (c) plant cover [126]; (d) slope [117] and (e) land use type [127].

Critical depth of trampling-induced compaction: The depth of trampling-induced soil compaction varies depending on animal weight and soil moisture and could range from 5 to 20 cm.

Ferrero and Lipiec [117] reported that most compaction effects were limited to the surface and intermediate depths (to a depth of 20 cm).

Animal trampling increased soil density at the first 5 cm soil depth and trampling affected soil properties to a depth of 20 cm, with the greatest effect in the top 5 cm [126,128].

Usman [128] suggested that trampling produced dense zones, which reduced water infiltration at a depth of 7.5 cm. The depth of this dense zone is very close to the depth of the hardpan detected by other researchers [130, 131].

Trampling intensity: Compared different grazing intensities (animal-unit-month per hectare, AUM/ha) and found that heavy (3 AUM/ha) to very heavy (4 AUM/ha) grazing pressure significantly increased surface runoff and soil loss and reduced infiltration, compared to light (0.6 AUM/ha) or moderate grazing (1.8 AUM/ha) [123]. However, fine-textured soils were more susceptible to trampling effects than coarse-textured soils. These results are somewhat different from the results reported by Donkor *et al.* [124] who showed that the same degree of soil compaction can be achieved by smaller numbers of animals grazing for a longer period or a large number of animals grazing for a short period. They compared the effects of high intensity, short-duration grazing (SDG, 4.16 AUM/ha) with moderate intensity, continuous grazing (CG, 2.08 AUM/ha) and concluded that grazing for short periods did not show any advantage over continuous grazing in improving soil physical characteristics and herbage. Different grazing techniques, such as traditional set-stocking (where sheep were grazed continuously for 17 weeks), controlled grazing (where sheep were temporarily removed from the enclosure when the topsoil was close to its plastic limit), and no grazing (where the pasture was mown to simulate grazing without trampling), were compared on a sandy clay loam (red duplex soil, Alfisol) growing a medic (*Medicago polymorpha*) pasture [132]. At the end of the grazing period, all soil structural attributes measured showed that topsoil structure under the controlled grazing practice was not only superior to that under the traditional set-stocking practice, but similar to that in the no grazing treatment.

Plant roots and soil compaction: The ability of plant roots to penetrate soil is restricted as soil strength increases and ceases entirely at 2.5 kPa [48, 49]. The inability of plant roots to penetrate compacted soil layers is well documented in the literature [134-136]. Hydrostatic pressure (Turgor) within the elongating region of the root provides the force necessary to push the root cap and meristematic region through the resisting soil. If the hydrostatic pressure is not sufficient to overcome wall resistance and soil impedance, elongation of that particular root tip ceases. Plant roots constitute a major source of soil organic matter when decomposed and while growing are capable of both creating and stabilizing useful structural features [137].

The effect of roots on soil structure depends on the species grown, soil constitution and environmental factors. The effect is also influenced by soil micro-flora associated with plant roots. Plants grown in compacted soil have shown a smaller number of lateral roots with less dry matter than plants grown under controlled conditions at both low and high soil water contents [138, 139].

Roots grown in more compact soil had smaller ratios of fresh to dry mass. Soil compaction can have adverse effects upon plants growing in the soil by [140]: (a) increasing the mechanical impedance to the growth of roots; (b) altering the extent and configuration of the pore space [140, 141]; and (c) aggravating root diseases such as common root rot of pea by decreasing drainage and thus providing more favorable soil water conditions for early infection of pea roots [143]. Diurnal changes in root diameter loosen and break down any compacted soil layer around them.

Using a Computer Assisted Tomography technique, showed that radish (*Raphanus* spp.) and lupin (*Lupinus* spp.) roots exhibit a temporary decrease in diameter after transpiration commences followed by a significant temporary increase [51]. This diurnal fluctuation in diameter destabilises soil and loosens the compaction. Roots of different crop species, as well as of cultivars within species, differ considerably in their ability to penetrate through hard soil layers [143]. Their response is related to the ability of the root system to overcome the soil strength limitations of compacted soil [134]. This was confirmed by Monroe and Kladivko [137] who reported that legumes are more effective for stabilizing soil structure than non-legumes, and lupins were the most efficient species.

Plant species that have the ability to penetrate soils with high strength usually possess a deep tap root system. Incorporating such species in the rotation is desirable to minimize the risks of subsoil compaction [144]. For example, in soils such as Vertisols with high shrink-swell potential, strong-rooted crops such as safflower (*Carthamus* spp.) could be used for biological soil loosening, through deep soil profile drying [145].

Variations between cultivars of the same species were generally small relative to differences between species and the plant species they used did not have the same ranking for structural efficacy in all soils but depended on initial structural status. They concluded that for particular plant/soil combinations roots may stabilize some soil fractions while destabilizing others [137].

Busscher [146] also reported that soybean (*Soja* spp.) CV PI 416937 possesses a superior genetic capability over

CV Essex to produce more root growth in soils with high penetration resistance. Accordingly they suggested that genetic improvement for root growth in soils with hard layers could potentially reduce dependence on tillage. However, crop management practices, such as tillage, use of heavy farm machinery, and crop rotation can also influence root growth by altering soil physical and morphological properties. If there is enough topsoil for root growth, roots will concentrate themselves there and increases in density of the subsoil may not result in significant decreases in yield.

Rosolem and Takahashi [55] studied the effects of soil subsurface compaction on root growth and nutrient uptake by soybean grown on sandy loam. They reported that sub-surface compaction led to an increase in root growth in the superficial soil layer with a corresponding quadratic decrease in the compacted layer. There was no effect of subsoil compaction on total root length or surface area, soybean growth or nutrition. Soybean root growth was decreased by 10% when the soil penetrometer resistances were 0.52 MPa (bulk density of 1.45 mg m^{-3}) and by 50% when the soil penetrometer resistances were 1.45 MPa (bulk density of 1.69 mg m^{-3}).

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