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Agricultural traffic impacts on soil

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Abstract

Alternate configurations of tires and tracks vary in their ability to generate tractive forces. These tractive elements also vary in the way that they impact the soil with some causing more soil disturbance than others. This soil disturbance includes soil compaction and rut formation which negatively impacts rainfall infiltration, rooting, and crop production while potentially increasing soil erosion and runoff. This paper will review a portion of the agricultural research that has been conducted related to soil impacts caused by the use of vehicle traffic in agricultural fields. Recommendations will also be made for ways to minimize the effects of vehicle traffic on soils when trafficking is necessary. These include: reducing axle load; reducing tractive element–soil contact stress by using radial tires, duals, and tracks; increasing soil drying prior to traffic; using conservation tillage systems which minimize vehicle traffic; using controlled traffic systems which eliminate random vehicle traffic across fields; and subsoiling to eliminate compacted soil profiles in crop growth zones. Soil compaction resulting from vehicle traffic may not be able to be completely eliminated, but it can be controlled and reduced through intelligent management of vehicle traffic.
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Keywords: Soil compaction; Subsoil; Axle load; Cone index; Bulk density

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1. Harmful effects of traffic

Agricultural production depends upon vehicle traffic. Without the ability to plant and harvest agricultural crops via tractors and combines, modern production practices could not exist. However, as vehicles have become progressively larger, they have also increased in their ability to damage the very medium that is responsible for producing and supporting agricultural crops. This damage may be visible due to aboveground deformation of the soil or it may be completely contained belowground and invisible from the soil surface. Either way, the effect of vehicle traffic can negatively impact crop production due to a compacted soil condition that is unable to adequately support a plant production system.

1.1. Soil compaction

Soil compaction may be the most devastating effect of vehicle traffic. Soil is composed of three components: air, water, and mineral. When a vehicle passes over the soil surface and soil compaction occurs, there is reduced volume available for air and water as the mineral components are pressed closer together. Soil compaction effects can last for years and may not be reduced by tillage, freezing or thawing [1]. Several factors can produce soil compaction.

1. *Soils predisposed to compaction*. Soil texture, or particle size distribution, may determine the self-compactability of a soil. A poorly graded soil with several finer particle sizes present will have less of an ability to compact as opposed to a well graded soil with a uniform distribution of particle sizes over the entire range of diameter classes [2,3].
2. *Soil loosened by tillage*. These soils which may have recently been tilled have no inherent strength and are not able to withstand the compressive forces exerted by vehicle traffic.
3. *Moist or wet soils*. These soils possess reduced soil strength and may be subject to soil compaction if vehicle traffic is applied when they are near field capacity. Soils also may get to the point where increased moisture will decrease the density of the soil due to swelling of clay particles thereby increasing sliding action between soil particles and reducing compaction.
4. *Increased vehicle loads*. As vehicle mass and weight increase, the load on the soil has also increased, thus promoting soil compaction. Large tractors, grain carts, manure spreaders, and combines can excessively compact soil.
5. *Repeated loadings*. Smaller loads exhibited from small tractors and other field equipment may also compact the soil if they are applied repeatedly in the same location.

Two measures of soil compaction that are commonly used are soil bulk density and cone index. Soil bulk density is a measure of the mass of soil per unit volume. As soil compaction occurs, the bulk density increases due to constant mass and reduced volume. Soil compaction naturally varies with soil type; sandy soils have naturally higher bulk densities than clay soils due to the many small pores associated with clays. Bulk density values of clays, clay loams, and silt loams normally range from 1.00 to 1.60 Mg/m^3 depending upon their condition and history [4]. Sands and sandy loams normally range from 1.20 to 1.80 Mg/m^3. Compacted soils may exhibit bulk density values of near 2.00 Mg/m^3 if severely trafficked.

Cone index is measured with a soil cone penetrometer which is defined by ASAE Standard S313.3 [5] and ASAE Standard EP542 [6]. These documents provide details on the construction and use of the soil cone penetrometer. The unit is composed of a 30° cone connected to a rod. A handle on the upper end is used to force the cone into the soil. Some method of measuring insertion force is included with the unit. Cone index is defined by the insertion force divided by the cross-sectional area of the base of the cone. As the pressures exceed 2 MPa [7,8], root growth has been shown to be restricted to varying degrees.

Cone index has two main advantages over bulk density measurements. First, they are easier to obtain requiring significantly reduced time to quantify the entire soil profile. The process can be automated and the entire zone surrounding a row can be quickly sampled for excessive soil compaction. Raper et al. [9] developed a multiple-probe soil cone penetrometer system that could quickly measure cone index across the row from a trafficked row middle to an untrafficked row middle (Fig. 1). Second, cone index measurements can be compared across soil types much easier than bulk density measurements. One significant disadvantage is that cone index measurements are greatly affected by soil moisture. Efforts should be made when attempting to compare between different soil types to obtain data at near field

Fig. 1. Multiple-probe soil cone penetrometer system developed at the USDA-ARS National Soil Dynamics Laboratory in Auburn, AL to measure cone index across the row from a trafficked row middle to an untrafficked row middle.

capacity when soil moisture is extremely high. Some researchers have found that cone index is more sensitive to increased vehicle traffic than bulk density [10].

Trafficked row middles are usually the areas of the field which are subject to the most intensive vehicle traffic. They typically have higher bulk density than nearby untrafficked row middles or areas under the row which may have been loosened by tillage. Kaspar et al. [11] found increased bulk density values in all trafficked row middles as opposed to the untracked row middles in Iowa. Also in Iowa, Hamlett et al. [12] found values of soil bulk density of between 1.10 and 1.40 Mg/m^3 for untrafficked and trafficked row middles, respectively, down to a depth of 30 cm. In a shallow depth range of 0–15 cm, Voorhees and Lindstrom [13] found increased bulk density in a Nicolett silty clay loam in Minnesota of between 1.40 and 1.65 Mg/m^3 for trafficked soils compared to 1.10 to 1.40 Mg/m^3 for untrafficked soils. Wagger and Denton [14] found that bulk density was significantly higher in trafficked row middles than untrafficked row middles (1.74 vs. 1.52 Mg/m^3) for a Golsboro fine sandy loam soil in North Carolina.

Similar to bulk density, greater cone index values are commonly observed in trafficked areas. Hamlett et al. [12] found elevated values of cone index for trafficked row middles compared to untrafficked row middles. Coates [15] found during the first three years of a trial that higher cone index values were found in trafficked row middles as opposed to beds or untrafficked row middles. Raper et al. [16] found that after five years in a controlled traffic cropping system, cone index was dramatically reduced in the untrafficked row middle as compared to the trafficked row middle down to depths of 0.45 m. Further reductions in cone index were found in the row position which had been in-row subsoiled [17] (Fig. 2).

Soil bulk density and cone index have been conclusively proven to increase as the magnitude and intensity of vehicle traffic increased. Oftentimes, these increases in soil compaction have been found to reduce rooting and crop yield, but occasionally weather conditions or prevalent soil conditions prevent significant cause–effect relationships from being found.

1.2. Rutting

One of the first visible signs that the soil is being harmed by vehicle traffic is excessive deformation of the trafficked area or rutting [18]. Rutting often occurs when traffic is applied to soil when it is in a compactable condition (Fig. 3). These extremely compactable conditions are present when the soil strength has been reduced either by loosening due to tillage or increased soil moisture due to recent rainfall or irrigation events. Several studies conducted at the USDA-ARS National Soil Dynamics Laboratory in Auburn, AL using soil bins filled with sandy loam and clay loam soils indicated that increased axle load and inflation pressure increased rut depth [19,20]. Raper and co-workers [19] additionally found that overall deformed rut cross-sectional area was increased by increased axle load. However, inflation pressure did not have the same effect. Increased inflation pressure was found to reduce rut width while increasing rutting depth, thereby canceling out the effect of inflation pressure on the deformed rut cross-sectional area.

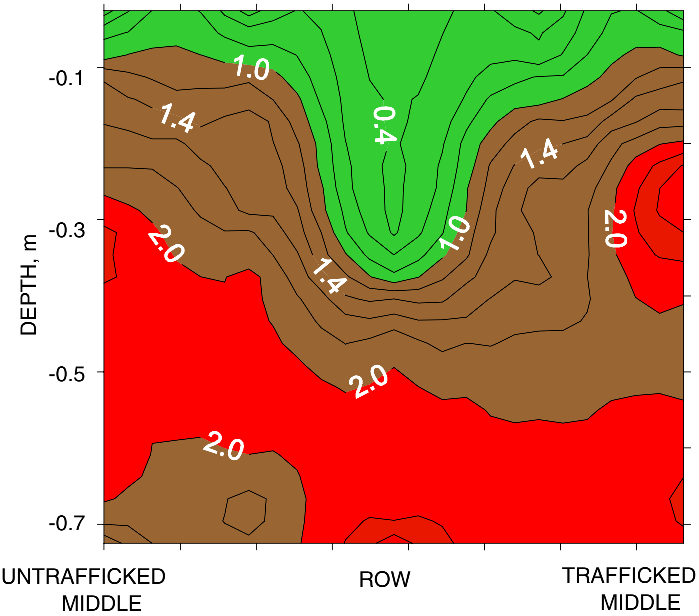

Fig. 2. Cone index profile across the row in sandy loam soils when plots received surface tillage, in-row subsoiling, and traffic on the right side. Numbers on graph indicate cone index (MPa) (from [17]).

Fig. 3. Excessive rutting caused by narrow high pressure highway tires.

Ruts are often seen as the remnant of rear tractor tires passing across the soil. However, Pearman et al. [21] found that rut depth was greatest under the front tire when it was operated in a loose soil condition above a hardpan as compared to both the inner and outer rear dual tires. Equivalent loads applied to the front and rear of the tractor coupled with smaller tires on the front caused increased rut depth and soil damage for the front tires.

It is important to note that even though rutting may be an indication of soil damage from vehicle traffic, a soil may exhibit no rutting and still be significantly affected by soil compaction. Tillage and weathering can reduce past ruts down to the soil surface where they are invisible. Another possibility is that rutting may not be noticed due to raised beds or rows of nearby crops.

1.3. Reduced infiltration and increased erosion

Even though ruts are a visible sign of traffic, the damage from rutting may actually occur later when rainfall occurs and a twofold problem develops. Rainfall would not be able to infiltrate due to excessive soil compaction and increased surface sealing caused by vehicle traffic. This rainfall would not be available for crop production later on during the growing season when soil moisture may be inadequate [1]. Gaultney et al. [3] found that water stood noticeably longer on compacted plots. Kaspar et al. [11] found increased runoff rates for a Clarion loam soil in Iowa for interrow wheel traffic tracks for three consecutive years during 1996–1998 as compared to untrafficked row middles. The erosion rate for the trafficked row middles was more than double that of the untrafficked row middle.

Potter et al. [22] found that wheel traffic greatly reduced the rate of water infiltration in Texas on a Houston Black clay soil (vertisol). They used a controlled traffic system to raise crops on wide beds and found that the trafficked row middles functioned as conduits for surface runoff. Hamlett et al. [12] found that infiltration in trafficked row middles was reduced significantly in Iowa on a Nicolett silt loam soil when compared to nearby untrafficked row middles. They also found that soil moisture near the surface was reduced by vehicle traffic, therefore, reduced moisture was available for plant growth.

Reduced infiltration resulting from compaction may not always have negative effects. Some researchers have used furrow compaction to reduce infiltration purposely in order to more efficiently use irrigation water. A study [23] on infiltration of irrigation water found that furrow compaction caused by vehicle traffic reduced intake by 18–27% on a Pullman clay loam in Texas. Allen and Musick [24] also found on the same soils that one and two passes with a light tractor (4.1 Mg) reduced furrow infiltration by 23% and 33% while one and two passes with a large tractor (8.2 Mg) reduced furrow infiltration by 38% and 43%.

Cultivating wheel tracks may provide for increased infiltration. Basher and Ross [25] found on a Dystric Nitosols clay loam soil in New Zealand that wheel tracks had much less infiltration than beds and greatly increased runoff and erosion. However, they found that when the wheel tracks were cultivated, the erosion rates were reduced from 21 Mg/ha to 1 Mg/ha. All soils may not respond in a similar manner. Voorhes et al. [1] reported that plots in Minnesota showed that uncompacted row middles absorbed most rainfall with minimal runoff and erosion while compacted row middles were stable to erosion, but allowed great amounts of water runoff.

1.4. Rooting restrictions

Vehicle traffic reduces pore space and increases bulk density of soils. Plant roots forced to grow in this compacted soil environment suffer because of the increased mechanical impedance and decreased oxygen availability [26]. One of the first studies that investigated reduced root growth as a function of soil compaction was Taylor and Gardner [7]. They forced a 0.48 cm diameter cylindrical penetrometer tip 0.5 cm into the soil surface as a measure of soil strength. This paper concluded that soil strength – not soil bulk density – was the critical impedance factor controlling root penetration in the sandy soils of the Southern Great Plains. They found a soil strength (2.96 MPa) at which no roots penetrated and was valid no matter if the strength was caused by increased bulk density or by decreased soil moisture. Using the same methodology and equipment, Taylor et al. [27] investigated the effect of various soil types on root growth. Their results showed that no taproots penetrated through cores with strengths greater than 2.5 MPa for four different soil types.

Taylor and Ratliff [28] conducted research using a 60° cone on a 0.318 cm diameter rod to measure penetration rates at which roots stop growing based on soil strength and soil moisture. They found that an increase in soil strength from 0 to 1.0 MPa reduced cotton elongation rates by 62% and peanuts by 29%. A critical limit of 2.7 MPa for cotton roots and 4.5 MPa for peanuts was determined that would substantially restrict root growth. They also mentioned that increased soil strength increased the root diameters of both cotton and peanuts.

Some studies have been conducted in soils where vehicle traffic has been applied uniformly across the soil surface. Raghavan et al. [29] found that rooting depth decreased from 90 cm in plots with no traffic to 37 cm in plots where 15 passes of vehicle traffic occurred with contact pressures of 62 kPa.

Most production systems do not uniformly traffic the entire soil surface, but concentrate the vehicle traffic on one side of the row. Kaspar et al. [11] found that wheel traffic significantly reduced corn root growth in the upper 30 cm as compared to the untrafficked side of the row. Some researchers have suggested that the lack of a crop response to wheel traffic may be due to increased root growth on the untrafficked side of the row to compensate for decreased root growth on the trafficked side of the row [30].

1.5. Crop reductions

Yield reductions are commonly found with areas severely compacted by vehicle traffic. Raghavan et al. [31] investigated applications of repeated traffic of 1, 5, 10, and 15 passes with contact pressures of 31, 41, and 62 kPa and a zero traffic treatment on St. Rosalie clay soil in Quebec, Canada. They found yield reductions of 40–50% with higher contact pressures and multiple passes. Gameda et al. [32] reported that applications of axle loads of 10 and 18 Mg increased bulk density up to 1.79 Mg/m^3 at depths of 2–30 cm in a clay soil in Canada. They found grain yield reductions of 18–27% under optimal weather conditions and 55–86% under adverse weather conditions.

Hammel [33] applied axle loads of 5, 10, and 20 Mg on a silt loam soil in Idaho. They found that bulk density and cone index were increased in the subsoil to depths of 75 cm and that these increases persisted for 3 years. Crop yields were not affected by a 10 Mg load, but compaction resulting from a 20 Mg load reduced root growth and crop growth during dry years. Lowery and Schuler [34] applied axle loads of 8 and 12.5 Mg on two soil types, a silt loam and silty clay soil. They found that corn grain yields were reduced the first year at both sites, and on the second and fourth years at the silt loam site and silty clay site, respectively.

Gaultney et al. [3] found 50% corn yield reductions with severe compaction and 25% yield reductions with moderate compaction. Their different degrees of compaction were obtained by driving a tractor back and forth over plots until moderately and severely compacted bulk densities of 1.76 Mg/m^3 and 1.82 Mg/m^3 were achieved. Uncompacted values of bulk density were 1.71 Mg/m^3. Ngunjiri and Siemens [35] found that corn yields on a Thorp silt loam soil in Illinois with wheel traffic applied over the entire plot area averaged 9.8 Mg/ha which was significantly lower than yields for no traffic (12.5 Mg/ha) and with traffic between and on rows (12.6 Mg/ha). Wheel traffic of an 8.5 Mg axle load increased both soil bulk density and cone index to a depth of 30 cm. The location of wheel traffic did not affect population, but did increase the number of barren stalks. Reduced growth and shorter plant height were also indicative of wheel traffic. Root density was not statistically affected by wheel traffic, but root distribution was.

Soil compaction does not always decrease crop yields. Depending upon the climatic condition, yields can be slightly improved with moderate compaction. Voorhees [36] studied the effect of wheel tracks on bulk density, cone index, and soybean yield on a Webster clay loam soil in Minnesota. They found that five years worth of compaction from vehicle traffic on both sides of the row produced increased levels of bulk density and cone index to depths of 30 cm. However, when these rows were compared with nearby rows with no traffic on either side of the row, only two of five years showed yield decreases from compaction. In two of the other years, the soybean yields were actually decreased by having no vehicle traffic nearby. Voorhees et al. [37] reported that preplant wheel traffic both increased and decreased wheat yields depending upon the precipitation during the growing season. Bicki and Siemens [38] found that in dry years, corn yields were greater in compacted plots than from plots with no compaction. With more favorable moisture conditions, compaction was found to decrease yields.

2. Minimization of traffic effects

Eliminating the effect of vehicle traffic on agricultural crop production is impossible. The ability to propel a vehicle through the field to conduct field operations is necessary and can not be eliminated. However, methods can be utilized to reduce the effect of vehicle traffic on crop production. These include reducing the soil's ability to compact, reducing the amount of vehicle traffic, reducing the size of the vehicles, controlling the traffic, minimizing tractive element–soil contact stress, or subsoiling.

Natural processes including freezing and thawing have been suggested as a natural cure for soil compaction but have not proven to be completely effective.

2.1. Reduced axle load

Early soil compaction research that focused on vehicle traffic recognized that soil compaction in the upper portion of the soil profile was controlled by the specific pressure at the surface and that soil compaction in the lower portion of the soil profile was controlled by the amount of load [39]. Taylor et al. [40] in a soil bin experiment verified that increased axle load was responsible for increased soil pressures at 18, 30, and 50-cm depths despite the fact that both loads had equal soil surface pressures. These studies point to the need to reduce vehicle size as a method of reducing the ability of a vehicle to cause deep subsoil compaction. As opposed to surface compaction, which can mostly be eliminated with surface tillage or management system, subsoil compaction is longer lasting and may be permanent.

Numerous experiments have been conducted with varying axle loads that completely covered the plot area in order to assess soil properties and crop production resulting from these loads. Voorhees et al. [41] applied loads of 9 and 18 Mg in two soil types in Minnesota. They found that little change occurred in the subsoil when it was dry; however, when it became wet, bulk density was increased significantly. Compaction from the higher load penetrated deeper into the subsoil and caused slightly higher values of bulk density, especially in the wetted condition. Alakukku and Elonen [42] found that compaction of clay soil caused by axle loads of 16 or 19 Mg penetrated to depths of 50 cm and resulted in measurable increases in soil compaction six years later. Ablas et al. [43] found that axle loads of 10 Mg and 5 Mg reduced silage yield by 15% and 4%, respectively, on a sandy soil in the Netherlands. Gameda et al. [44] reported that compactive loads of 12 and 20 Mg on a clay soil in Canada caused significant increases in bulk density, reductions in grain yield for 6 years, and reductions in total plant dry matter yield for 4 years following load application. Hammel [33] found that crop yields were not affected by a 10 Mg load in a silt loam soil, but compaction resulting from the 20 Mg load reduced root growth and crop growth during dry years. Lowery and Schuler [34] reported on compaction caused by 8 and 12.5 Mg axle loads on two soil types in Wisconsin. They found dramatically increased cone index measurements with increasing axle loads.

Bailey et al. [45] studied soil stresses and bulk densities caused by radial tires operated in a soil bin in two soil types, a Norfolk sandy loam soil and a Decatur clay loam soil. They operated the tire at two different levels of rated load with the correct inflation pressure taken from the tire manufacturer's published load tables and at two other combinations of load and inflation pressure representing over-inflated and under-inflated conditions. They found that increased axle load at constant inflation pressure increased soil stresses, soil bulk density at shallow depths, and at depths near the soil hardpan (Fig. 4).

Hakansson and Reeder [46] stated that subsoil compaction deeper than 40 cm may be considered permanent even in clay soils with significant freeze–thaw cycles.

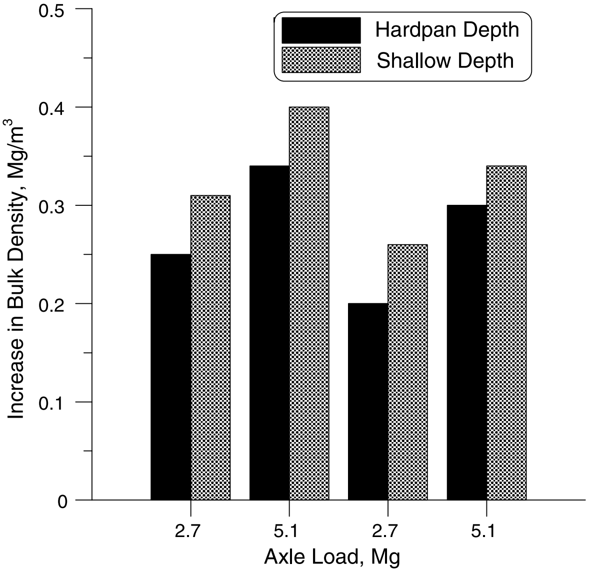

Fig. 4. Effect of axle load on increases in bulk density for two soils averaged across profiles (from [45]).

These authors reviewed the results of numerous experiments carried out on several continents to examine the effects of increased axle load on subsoil compaction and came to the conclusion, "when driving a vehicle on moist, arable soil, measurable compaction may be expected to a depth of at least 30 cm at an axle load of 4 Mg, 40 cm at 6 Mg, 50 cm at 10 Mg, and 60 cm or deeper at an axle load of 15 Mg or higher". Using these authors' conclusions, it seems reasonable to restrict axle loads to less than 6 Mg as a method of reducing subsoil compaction and keep the resulting compaction in the topsoil region where it can be managed.

2.2. Reduced tractive element–soil contact stress

Research into the use of radial tires for tractors has been ongoing since the early 1960's. Previously, the only alternative was bias-ply tires. However, radial tires offered a realistic alternative that increased the ground contact area thus increasing traction and reducing soil compaction [47]. Initial claims of radial tractor tires included improvements in traction of up to 20% that were proven in controlled soil bin tests [48]. Radial tires are even more advantageous as soil firmness improves as is typically found with conservation tillage systems [49].

The use of radial tractor tires coupled with reduced inflation pressures has been proven to reduce soil compaction. Raper et al. [50,19] found in soil bin tests on Norfolk sandy loam soils and Decatur clay loam soils that when inflation pressures are properly set on radial tractor tires, extreme soil-tire interface pressures are kept near the outer edges of the tire and are reduced from those measured under excessively inflated tires operating under similar loads (Fig. 5). Reduced cone index and bulk

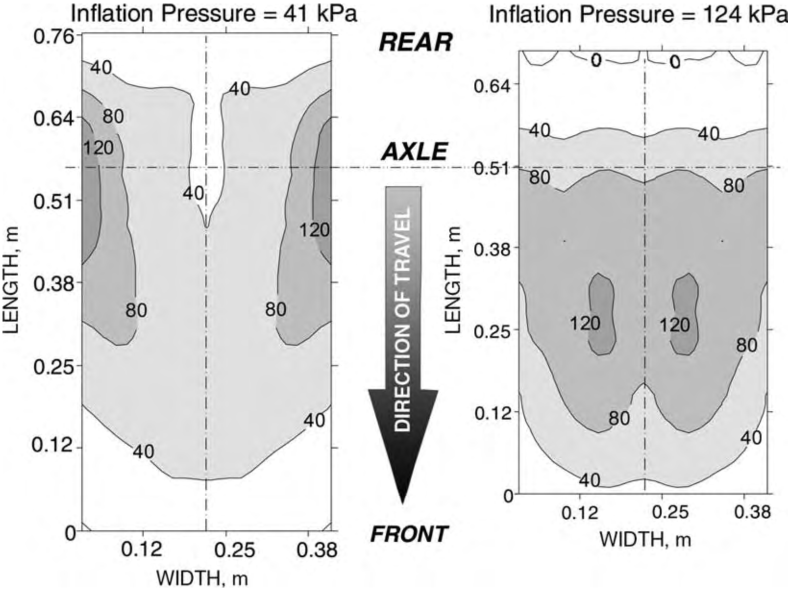

Fig. 5. Soil-tire interface pressures measured under the tire lugs as the 18.4R38 tire passed through a Norfolk sandy loam soil. The tire was loaded to an equivalent axle load of 2.7 Mg. Contours indicate pressures (kPa). (from [19]).

density measurements [45] were also found in the center of the wheel track when the radial tractor tire was properly inflated.

Using dual tires has been a widely used method of spreading the load over the soil surface.

Soil pressures measured under dual tires have shown that near the soil surface (0.18 m) similar pressures exist but at depths of near 0.5 m, the pressures are decreased by almost 50% by using dual tires instead of single tires [51,52]. One negative aspect of using duals, however, is that the soil compaction near the surface is increased in the area under the second tire from zero as when duals would not be used to some value greater than zero when duals are used. Dual tires essentially traffic twice the width of the vehicle track and, depending upon the crop and cropping system, may cause excessive surface compaction.

Increasing tire size may offer a method to increase the area of a tire that is in contact with the soil. Assuming equal widths of a tire, larger tires should produce an increased contact area with the soil due to their increased contact length. Few experiments, however, have investigated this hypothesis. Koger et al. [53] examined tire size in a soil bin experiment at the USDA-ARS NSDL at Auburn, AL. They found, however, that increased tire size was responsible for increased bulk density and cone index in several of their tests. They concluded that tire size alone was not responsible for increased compaction because along with the increased tire size was also increased stiffness due to increased number of plys. Murosky and Hassan [54] found that increased tire size (width) did reduce rutting, cone index, and bulk density due to the ability of the tire to spread the load out on the soil surface. Chi and Tessier [55] tested various tire configurations on a truck with a liquid manure tank. They found that high flotation tires produced shallower ruts and more uniform compaction near the soil surface than high inflation pressure radial tires.

Increasing the number of axles under trailers has also been hypothesized as a potential solution to reduce the axle load on the soil surface and thus reduce the soil contact stress. Bedard et al. [56] found, however, that oversize tires were more effective in reducing bulk density and cone index in the soil profile than increasing the number of axles from 2 to 3. However, the oversize tires had an increased width and thus produced a wider zone of soil compaction which again could be detrimental for certain crops or cropping systems.

Tracks have also become a popular alternative for producers who have tried to increase the tractive efficiency of their vehicles and also to reduce soil compaction in their fields. A tracked vehicle has been proven to have higher tractive efficiency than either two-wheel drive or four-wheel drive tractors [57,58]. Taylor and Burt [59] compared a steel track, a rubber track, and a tire in a soil bin and concluded that greater bulk density and soil pressures were found for the tire. However, similar soil pressures have been measured under rubber-tracked and tired vehicles with similar mass [60]. Even though the average ground pressure exerted by the tracked vehicle was smaller due to its increased footprint, the data indicated that substantial peak pressures were exerted by rollers, which were similar in magnitude to those measured under tires.

Another option that has been suggested as a method of reducing soil compaction is to increase vehicle traffic speed. Vomocil et al. [61] used infiltration as a method of measuring the effects of vehicle traffic. They found that a reduction in speed also decreased infiltration, but they noted that infiltration was especially difficult to perform with side-by-side wheel marks. Vernikov [62] found that rut depth was decreased from 8.5 to 5 cm when traffic speed was increased from 6 to 20 km/h. Some researchers have hypothesized that increased bouncing of agricultural vehicles without suspension systems is responsible for the decreased measurements of soil compaction attributed to higher field speeds. Aboaba [63] studied this issue and found that even when bouncing was eliminated, the longer a roller remained on the soil, the greater the sinkage until it became asymptotic.

2.3. Increased soil drying

Increasing the resistance of soil to compaction can be accomplished by increasing soil strength, thus enabling the soil to better withstand the compacting effects of vehicle traffic. One method of increasing soil strength is to reduce soil moisture. Allowing the soil to dry may improve the ability of a soil to withstand compactive forces caused by vehicle traffic. Vomocil et al. [61] found that soil compaction was much more sensitive to changing soil moisture than it was to varying wheel speeds. They used infiltration rate as an indicator of soil compaction. Allen and Musick [10] reported that relatively moist soil (above 60% field capacity) during traffic greatly increased compaction and decreased infiltration, even for a relatively light 4.1 Mg tractor. Ekwue and Stone [64] reported that bulk density, penetration resistance, and shear strength of soils increased with increments in moisture content up to a point, but after peak values were achieved the soil values decreased with further moisture increases. Raghavan et al. [31] recommended that in a dry year, moderate compaction of the topsoil may be beneficial to crop yield, while in wet years, it is essential to limit traffic and compaction to an absolute minimum level. Voorhees et al. [41] found subsoil was unaffected by large axle loads when it was dry, but bulk density was increased significantly when the subsoil was wet and loads were applied.

2.4. Conservation tillage systems

Another method of increasing soil strength is through the use of conservation tillage systems. Sometimes no-tillage systems exhibit higher soil bulk density values than frequently tilled conventional tillage systems. Potter and Chichester [65] found increased values of bulk density and cone index in the upper 30 cm after 6 and 10 years of continuous no-till compared to a recently tilled soil. However, the no-tillage systems may have more macropores due to increased biological activity and promote higher rates of infiltration and increased water availability. These macropores may allow increased infiltration and in fact allow higher overall productivity due to increased soil moisture storage even though they have somewhat higher soil bulk density. Mostaghimi et al. [66] reported that no-till was effective in reducing runoff and sediment losses. Because of the higher bulk density, no-till systems may be also able to withstand higher compactive forces from vehicle traffic.

Some research has even suggested that soil compaction becomes unimportant when producers convert to no-tillage systems. Thomas et al. [67] reported that increased organic material in soils reduced their ability to compact. Organic matter accumulation in the surface 0–10 cm layer where conservation tillage has been practiced may lead to reduced compaction after several years. It also may lead to an increased amount of water in the soil profile that is available for crop use during the growing season [68].

Cover crops have also been found to provide a method of alleviating soil compaction. In a study in a Decatur silt loam in Alabama, Raper et al. [69,70] investigated subsoiling depth, subsoiling timing, and use of cover crops to alleviate soil compaction and improve crop yields. They found that cone index was reduced significantly by the use of cover crops, probably due to increased water infiltration and storage. Yields similar to conventional tillage were obtained by simply adding a cover crop which alleviated soil compaction. Ess et al. [71] investigated the effect of an intact cover crop on soil compaction of a silt loam soil in Virginia by repeated vehicle traffic of 1, 3, and 5 passes. Significantly reduced bulk density was found for plots that included a cover crop as compared to bare plots in the soil surface layer (2.5-7.5 cm) following multiple machine passes. Soil compaction appeared to be reduced by the root mass of the cover crop with little benefit seen from the aboveground biomass.

Perhaps the easiest method to reduce soil compaction is to reduce the number of times that vehicles are required to enter a field. Typically, in a conventional tillage system, several passes are necessary including: (1) initial primary tillage, (2) secondary tillage, (3) potential additional secondary tillage, (4) planting, (5) repeated spraying or cultivation operations throughout the growing season, and (6) harvest. Some researchers have estimated that 70% of the field may be trafficked by vehicle traffic in a conventional tillage system. Additionally, the first pass of a wheel on loose soil is responsible for about 85% of the total compaction [72]. Therefore, a producer using a conventional tillage system could easily traffic 70% of his field to 85% of the maximum compaction limit. It is easy to see why many producers who have used conventional tillage systems for many years are now reporting compacted soil conditions and potentially reduced yields.

A conservation tillage system can reduce the need for vehicle traffic in the field because there are fewer needs for tillage or cultivation operations. Often the only passes necessary for crop production using one of these systems is (1) planting, (2) spraying if necessary, (3) harvesting, and (4) cover crop establishment. The opportunities for soil compaction are reduced as less intensive vehicle trafficking is required.

2.5. Controlled traffic system

Another option for overall reduction of vehicle traffic in the field is to consider a form of controlled traffic. A controlled traffic system was defined by Taylor [73] as a crop production system in which the crop zone and the traffic lanes are distinctly and permanently separated. The traffic lanes are compacted and are able to withstand additional traffic without deforming or compacting. Tractive elements on compacted traffic lanes are also able to increase tractive efficiency and have higher flotation. The crop production zones in the center of the lanes are only used for plant growth and are not compacted by vehicle traffic. Soil compaction is virtually eliminated except for naturally occurring conditions and that caused by tillage implements.

Several attempts at developing a controlled traffic system have used existing agricultural tractors with increased wheel spacing. Williford [74] developed a cotton production system by using existing 6-row equipment with a wheel spacing of 2.5 m. They found significantly increased cotton yields in a Tunica clay in Mississippi over a 5-yr period from controlled-traffic plots. The use of such a system could reduce the need for annual deep tillage in Mississippi Delta soils. Colwick et al. [75] reported that in a silty clay loam soil in Mississippi when tractor traffic was controlled, the effect of initial subsoiling lasted for 3 years. Morrison [76] discussed several options for using normal tractors and harvesting equipment. He found that the most likely wheel spacings would be 1.5 m, 2.3 m, or 3.0 m, however, dual wheels (common on some tractors) would have to be eliminated and replaced by tandem wheels.

Specialized gantry-type machines have also been constructed and used to spread the loads over much wider crop growth zones as compared to normal agricultural tractors. Gebhardt et al. [77] developed a gantry machine which spanned 3.3 m for controlled traffic research. Another larger gantry unit with a 6-m wheel spacing was created at the USDA-ARS National Soil Dynamics Laboratory in Auburn, AL [78] for controlled traffic research (Fig. 6). Reduced values of cone index and bulk density have been found with the use of this gantry in Coastal Plain soils but

Fig. 6. Wide-frame tractive vehicle constructed at the USDA-ARS-NSDL in Auburn, AL for controlled traffic research.

corn, cotton, and soybean yield response varied depending upon year and rainfall [30,16,79].

As automatic steering systems which use satellite technology to accurately control agricultural equipment become widely available, the use of controlled traffic will undoubtedly become much more widely used. These systems currently have the capability of placing vehicle traffic in the same field location with 2–3 cm precision and are now gaining wide acceptance in American agriculture. Specially constructed and raised traffic paths will not be necessary as tires and tracks will automatically return to their same location and traffic the same soil.

2.6. Natural compaction alleviation

Many producers who live in climates with numerous or deep freeze–thaw cycles do not feel that they have any reason to fear traffic-induced soil compaction. Other producers have been told that drying and wetting cycles may have positive benefits that will alleviate soil compaction problems. These natural cycles may have some positive benefits, however, the long-lasting effects of vehicle-induced soil compaction are significant.

Voorhees [80] studied the compaction alleviation benefits associated with natural forces on a Nicollet silty clay loam soil in Minnesota. After five years of wheel-induced traffic, the plots were analyzed for changes in bulk density and cone index. Their results showed that natural weathering reduced cone index by 20–50% but had little effect on bulk density. In a later experiment, Voorhees et al. [41] found compaction persistence 4 years after application despite annual freezing to a 90 cm depth. Etana and Hakansson [81] found that compaction in Sweden in several clay soils caused by axle loads of 10 Mg, which had compacted the soil down to 50–60 cm, were unaffected by the normal annual freeze–thaw cycle which occurred to depths of 40–70 cm over an 11 year period. Kay et al. [82] evaluated bulk density changes in a silt loam and a clay loam soil in Ontario, Canada which occurred as a result of freeze–thaw cycles. They found that frost did heave the soils a significant amount during winter months, but the soils quickly reconsolidated upon thawing and returned to near prefreezing bulk densities prior to spring planting.

All of these studies point to the inefficiency of natural processes to eradicate soil compaction caused by vehicle traffic. Once vehicle traffic occurs, semi-permanent soil compaction results and can detrimentally affect crop yields for many years.

2.7. Subsoiling

When soil compaction has already occurred and must be reduced to allow proper root growth, tillage may be necessary to eradicate and manage severely compacted soils (Fig. 7). Tillage below depths of 35 cm is referred to as subsoiling [83]. Subsoiling combined with controlled traffic increased cotton yields in Tunica clay soils in Mississippi by 14.7% and 8.2% in nonirrigated and irrigated environments, respectively [84]. A study conducted in North China [85] found that subsoiling reduced bulk density in the top 40 cm of the soil profile, increased the number of large pores, and decreased the number of small pores. Water infiltration was improved due to the improved macroporosity. In a silty clay soil in New Zealand [86], subsoiling was found to reduce cone index values and improve forage yields by almost 20%. Gameda et al. [32] used subsoiling to attempt to alleviate soil compaction caused by applications of 10 and 18 Mg axle loads on a clay subsoil in Canada. They found that subsoiling improved soil structure and allowed corn grains yields to rebound to between 80% and 100% of yields in control plots.

Subsoiling should not excessively disrupt the soil surface. Conservation tillage practices that only require subsoiling beneath the row leave most of the soil surface

Fig. 7. Cotton grown without subsoiling is shown in middle four rows of plots. Larger plants on outside of plots benefited from subsoiling.

undisturbed while disrupting compacted soil profiles (Fig. 8). In-row subsoiling or strip-tillage was found to improve cotton yields by 22% in a Norfolk sandy loam soil in Alabama that had a well-developed hardpan and that was easily compactable, but did not improve yields on two other Alabama soils (Emory silt loam and a Lucedale sandy clam loam) [87]. Raper et al. [16] reported that on a sandy loam Coastal Plain soil, in-row subsoiling dramatically reduced cone index values and provided the greatest cotton yield potential. They also found that an initial complete subsoiling treatment that provided complete belowground soil disruption did not produce higher yields after 5 years.

Non-inversion subsoiling (another conservation tillage practice) commonly conducted with a bentleg subsoiler has resulted in decreased cone index and bulk density in a semi-arid Pullman clay loam in Texas [88]. Stubble-mulch tillage conducted following bentleg subsoiling diminished the benefits afforded to cone index and bulk density in this study. Schwab et al. [89] reported that non-inversion subsoiling or in-row subsoiling conducted in the fall of the year on a Decatur clay loam in Alabama resulted in the highest seed cotton yields; 16% greater than conventional tillage and 10% greater than strict no-tillage. A nearby experiment conducted during the same time period found that shallow in-row subsoiling conducted just below the depth of compaction decreased cone index and bulk density measurements compared to no-tillage systems [69,70]. Non-inversion subsoiling also provided for improved soil conditions in a pasture on a Harsells fine sandy loam soil in Alabama down to a depth of 32 cm [90].

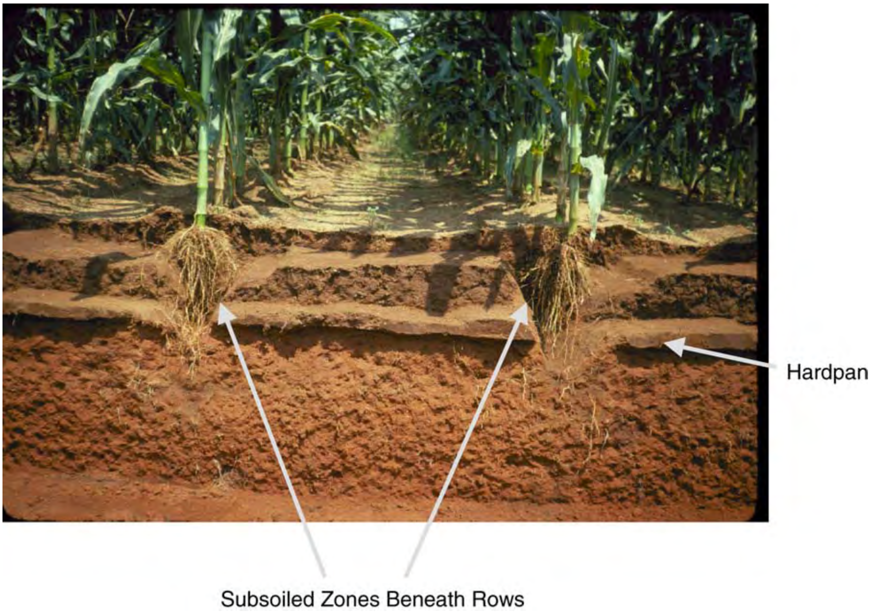

Fig. 8. In-row subsoiling, which is conducted beneath the crop rows and to depths sufficient to disrupt the hardpan, benefits the crop while leaving the areas between the rows relatively undisturbed.

When irrigation has been used, crop yield improvements have not always been found with subsoiling. In a southeastern Coastal Plains soil, Camp and Sadler [91] found that irrigation increased corn yields all years between 8% and 135% while subsoiling increased yield in only two years by 4–6%. In a Casa Grand silt loam soil in Arizona, Coates [92] found that cotton yields were not affected by subsoiling in an irrigated field. Aase et al. [8] reported that subsoiling did not increase runoff on furrow-irrigated land and did not improve crop growth and yield.

In some soils where severe compaction is not a problem, subsoiling may not result in higher yields. Gaultney et al. [3] found that subsoiling was ineffective in reducing the effects of compaction for Midwestern soils. On a clay loam soil in Minnesota [93], subsoiling was conducted in fall of 1988 and cropped to continuous corn from 1989 to 1991. Subsoiling had no effect on plant growth or crop yield over these seasons. Bulk density was initially reduced but the soil reconsolidated by the 1990 season.

Another aspect of subsoiling is to target the depth of subsoiling to the depth of compaction. Subsoiling at depths greater than necessary requires significant additional tillage energy and may reduce crop yields while covering excessive amounts of crop residue remaining on the soil surface. Also, loosening the soil to greater depths than necessary can promote future deeper compaction resulting from vehicle traffic. Raper et al. [69,70] found in a clay loam in Alabama that targeted depths of subsoiling to the depth of compaction resulted in optimum yields while deeper depths of subsoiling resulted in reduced yields. This response was found in a soil type that has not traditionally responded positively to subsoiling.

3. Summary

Soil compaction is a very complex process as can be illustrated by the numerous citations available on the subject. A direct cause–effect relationship between vehicle traffic and crop response is difficult to establish due to existing soil conditions, differences in climate, differences in annual precipitation, differences in soils, spatial variability within fields, differences in crops, differences in crop varieties, and differences between various forms of vehicle traffic elements. In summary, the following broad recommendations can be made to producers who are trying to reduce the effects of vehicle traffic in their agricultural fields in my perceived level of importance:

(a) Only traffic when soil moisture is less than 60% of field capacity. Vehicle traffic conducted when soil moisture is greater than approximately 60% of field capacity can lead to excessive soil compaction that may be battled for many cropping seasons. Or worse, the damage may be permanent.
(b) Adopt a conservation tillage system that minimizes tracks across fields and seeks to build levels of organic matter that may help to minimize vehicle traffic effects.
(c) Adopt a controlled traffic system that will limit vehicle traffic to certain areas within the field thus reducing random traffic.

(d) Reduce axle load by minimizing the size of the vehicle necessary for the field activity.
(e) Use radial tires which maximum the size of the tire footprint and reduce soil compaction while increasing tractive effort.
(f) Use the minimally recommended inflation pressure for radial tires from tire manufacturer's load-inflation pressure tables.
(g) Consider the overall benefits of tracked vehicles while recognizing that peak pressures that occur under tracks may be similar to peak pressures that occur under radial tires for similar-sized vehicles.
(h) Reduce contact pressure by using duals while recognizing the wider area of compaction associated with dual tires.
(i) Finally, if compaction measurements indicate that vehicle traffic has caused soil compaction, subsoil to shallowest depth possible to remove compacted soil layers. The subsoiler system used should minimally disrupt the soil surface, maintain large amounts of crop residue on the soil surface, and be targeted toward the crop growth zone.

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