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SOIL COMPACTION: HOW TO DO IT, UNDO IT, OR AVOID DOING IT

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ABSTRACT. *Soil compaction reduces rooting, infiltration, water storage, aeration, drainage, and crop growth. Soil compaction has been studied intensively for more than a century, and yet we still struggle with the effect that soil compaction has on crop production and the environment. In this article, we attempt to present the primary causes of soil compaction including trafficking weak soil, excessive loads, and soils that are somewhat predisposed to soil compaction. We also offer suggestions on methods of alleviating soil compaction, which vary from gradual improvement using conservation tillage systems to the immediate improvement offered by subsoiling. Additionally, we cover methods that producers can use to avoid compacting their soil, including reducing their axle load, using radial tires and maintaining proper inflation pressure, duals, tracks, and controlling their traffic. Unfortunately, few if any of our suggestions could be used to cure soil compaction because as long as vehicles are used to plant and harvest crops on the same soil that is used to produce crops, there will continue to be soil compaction and an endless battle to reduce its ill effects.*

Keywords. Soil compaction, Subsoiling, Soil density, Cone index, Axle load, Controlled traffic.

Soil compaction is a densification and reduction in porosity, associated with changes to the soil structure and (usually) an increase in strength and a reduction in hydraulic conductivity (Soane and van Ouwerkerk, 1994a).

Soil compaction causes problems in crop and forest production worldwide (Soane and van Ouwerkerk, 1994b) and thus has received much attention in research and extension. The compaction of soil should be avoided because:

- it creates a poor environment for roots: poor aeration, waterlogging, and excessive soil strength limiting root growth (Taylor and Gardner, 1963; Stepniewski et al., 1994), a reduced non-limiting water range (Letey, 1985; McKenzie and McBratney, 2001); and, sometimes failure of roots to exploit all the soil [right-angled roots (fig. 1), etc.].
- can lead to excessive runoff and erosion (Fleige and Horn, 2000).

Sometimes, however, compaction is desirable, because it can lead to:

- improved seed-soil contact, and hence better germination and growth of the seedling (Radford and Nielsen, 1985);
- improved crop yields during extremely dry years (Raghavan et al., 1979);
- better roadways (farm roads, lanes between beds), dam bases;
- reduced deep drainage, for example in flooded rice systems (Humphreys et al., 1992).

The literature abounds with textbooks (Barnes et al., 1971; McKyes, 1985; Soane and van Ouwerkerk, 1994a) and conference proceedings (Arvidsson et al., 2000; Horn et al., 2000). Compaction articles appear frequently in journals such as *Soil and Tillage Research*, *Journal of Terramechanics*, *Transactions of ASAE*, and *Applied Engineering in Agriculture*. Hamza and Anderson (2005) and Raper (2005) recently reviewed the literature.

In this review, we do not attempt to review the whole of the literature. Rather, we pick out the main threads, and examine compaction from a practical viewpoint – how to do it, undo it, or avoid doing it. We also examine the need for further research and offer some suggestions.

Figure 1. Cotton tap root deformed by soil compaction at multiple depths.

DOING IT (CAUSES)

Soil compacts when it is too weak to bear the stresses imposed on it – which could mean that the soil is weak, or that the load causing the stresses is excessive, or both. Excessive loads may arise from artificial (tractors and other vehicles, implements) and natural causes (animals, trees). Weak soil may arise when it is wet, or loose, or both.

WEAK SOIL

Soil is ideally suited for root growth when it is fairly moist, well aerated, and is not too strong to impede root growth. In this condition, it is generally too weak to bear heavier agricultural traffic. It is a matter of common observation as well as research findings that a moist, freshly tilled seedbed will compact greatly if driven upon (Botta et al., 2002).

Soil strength varies greatly, being determined mainly by the moisture content and the density. The soil composition also affects soil strength, primarily through its influence on soil moisture content and density.

Moisture Content Effect

Soil moisture content is generally singled out as the most important influence on soil strength and hence on compaction (Hamza and Anderson, 2005). In Vertisols (essentially heavy clays, with a high clay content at all depths from the surface to 50 cm or more, and often cracking when dry unless irrigated or cultivated), strength can vary by two orders of magnitude over the range of moisture contents (for a given density) commonly experienced in agricultural operations (fig. 2; Kirby, 1991a). Other soils behave similarly, showing severe soil compaction when wet, but resisting vehicle traffic quite effectively when dry (Voorhees et al., 1986; Allen and Musick, 1997). At the one extreme, these soils can be strong enough to bear the pressures of agricultural vehicles without showing signs of their passage. At the other extreme, there is intensive compaction and rut formation. Other soils may not show the extreme variation in strength displayed by Vertisols, but nevertheless, moisture content is the most important determinant of strength in most soils.

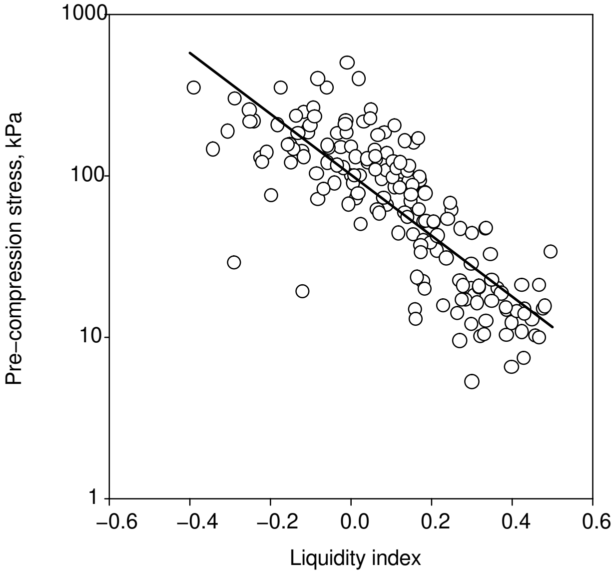

Figure 2. Precompression strength of a range of vertisols as a function of liquidity index. The line is the best fit functional regression line at the mean void ratio (Kirby, 1991a), and has an R^2 of about 0.7. The precompression strength equals the stress at which a vehicle will start to compact the soil and is thus the most direct measure of strength to resist compaction (Kirby, 1991b). The liquidity index is a normalized moisture content and so has a value of zero at the plastic limit, and it is negative at moisture contents drier than the plastic limit, which enables soils of a range of liquid and plastic limits to be plotted on the same moisture related scale. It is defined as Liquidity Index = (Moisture Content – Plastic Limit) / (Liquid Limit – Plastic Limit). Note that at the plastic limit (liquidity index of zero), the precompression stress is about 100 kPa, which is similar to the stress imposed by mid-range agricultural vehicles.

Although wet soils are weaker, very wet soils technically do not compact (Ekwue and Stone, 1995). Compaction is densification through the expulsion of air, and therefore by definition a saturated soil cannot compact. In this very weak state, however, tires and implements will smear the soil intensively (Davies et al., 1972), an action which disrupts pore continuity. This leads to reduced hydraulic conductivity and may be more deleterious to root growth than compaction.

Density Effect

In Australian Vertisols, soil strength increases an order of magnitude over the range of densities (for a given moisture content) commonly experienced in agricultural operations (fig. 3; Kirby, 1991a). The effect is smaller than the effect of varying moisture content, but is nevertheless an important control on soil strength. Again, the soil varies from a condition in which it is strong enough to bear traffic to one in which traffic will greatly compact it.

Figure 2 shows that the plastic limit (see next page) corresponds to a precompression strength of about 100 kPa, which is approximately the stress imposed by many agricultural vehicles. As a result, we conclude that at the plastic limit soil is able to bear the stress of many vehicles without excessive compaction, but heavier vehicles will compact the

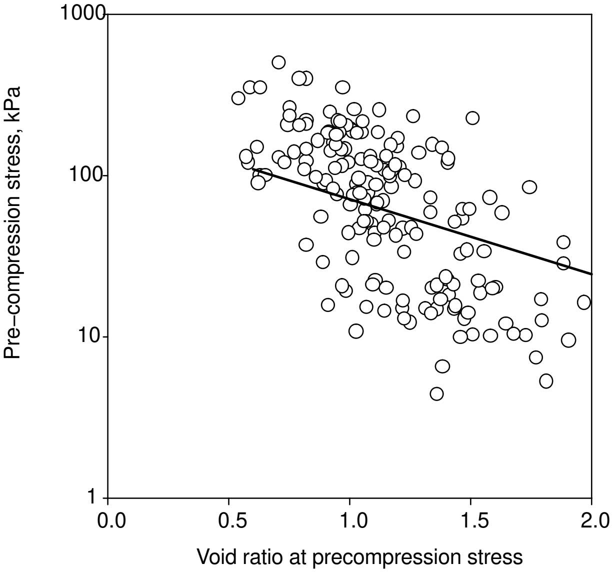

Figure 3. Precompression strength of a range of soils as a function of void ratio. The line is the best fit functional regression line at the mean liquidity index (Kirby, 1991a) , and has an R^2 of about 0.41. These data are from the same dataset as those in figure 2, and the best fit line is in fact a plane on a 3D plot. The void ratio is defined as the volume of voids in the soil divided by the volume of solids, and so is inversely related to the density: the bulk density at a void ratio of 0.6 is about 1.85 Mg/m^3, and at a void ratio of 2 is about 1.35 Mg/m^3. The precompression stress is defined in terms of void ratio (Kirby, 1991b), hence the use of void ratio rather than density.

Plastic Limit

The plastic limit is a readily measured index of soil condition, defined as the moisture content dividing a plastic state from a rigid state, and corresponding to a liquidity index of zero. In the field, a quick test can be used to judge whether soil is wetter than, at, or drier than the plastic limit. Work a small ball of soil (half the size of a golf ball) in the hand, and then roll a part of it into a thread or worm between two hands.

- If a long, thin thread (about 5-cm by 3- to 5-mm diameter) is rolled easily, the soil is wetter than the plastic limit. Compaction will result from traffic by many, perhaps most, vehicles.
- If the soil cannot be rolled but smears easily, then it is much wetter than the plastic limit. Compaction will result from traffic by virtually all vehicles.
- If the soil cannot be rolled into a thread, but crumbles or breaks into hard crumbs, it is drier than the plastic limit. Compaction is unlikely to occur and is unlikely to be severe.
- If the soil can just be rolled without crumbling, but is "on the edge" of crumbling, it is at about the plastic limit. Some vehicles will compact the soil, and some lower ground pressure vehicles will not.

These guidelines are rough, since the field test is a rough one, but they are nevertheless useful. The laboratory form of the test is similar but performed under more controlled and exacting conditions, and it is followed by an accurate determination of the moisture content of the soil.

soil. The plastic limit also corresponds to the ideal state for tilling soil (Dexter, 1988).

Soil strength is rarely constant with depth, usually increasing with increasing depth and sometimes showing a peak at the plowpan depth (Schafer-Landefeld et al., 2004). Thus, soil might be too weak in the surface, and compact there, while being sufficiently strong to resist compaction at depth. When the soil is weak at depth, compaction can result from vehicle traffic, and it is generally harder to reverse than compaction at the surface.

Some soils may naturally return after tillage to a compacted state that will significantly impede root growth. Their particle size distribution may place them at risk for 'natural' soil compaction as opposed to 'vehicle-induced' soil compaction. A well-graded soil with a uniform distribution of particle sizes over the entire range of diameter classes (such as well-graded loams) may naturally form a compacted layer as opposed to a poorly-graded soil with several finer particle sizes present (such as a sand or a silt) which is less likely to compact (Gaultney et al., 1982; Craul, 1994).

EXCESSIVE LOADS/EXCESSIVE STRESSES

Compaction is determined by three broad factors: the severity at the surface depends on the stress exerted at the surface; the impact at depth depends on the stress exerted at depth which is in turn related to the gross mass compacting the soil; both surface and deep impacts increases with repeated loading.

Severity of Compaction at the Surface

Stresses beneath tires and tracks of agricultural vehicles have been measured by many workers, both in laboratory soil bins and in the field (Kirby and Zoz, 1997). Stresses at the tire-soil contact generally range from about 50 kPa (under tracks and wide or dual tires) to 300 kPa or more (narrow tires with heavy vehicles, such as cotton pickers) (Kirby and Blunden, 1992).

This stress range is similar to the range of strengths with which soil may bear the stresses. Stresses at the top end of the range (heavy vehicles on small/narrow tires exerting pressures of 300 kPa or more) are greater than the soil strength except when the soil is in the driest condition (within the range usual in agriculture). Stresses at the bottom end of the range, will only compact soil that is wet and weak, but will not compact soil in an intermediate condition. Note, however, that any vehicle will compact soil that is weak enough.

Thus, compaction at the surface will always be more severe under a greater stress. For some combinations of stresses and soil strengths, a smaller stress may not compact the soil at all while a larger stress may exceed the strength threshold and cause compaction.

Impact at Depth

Isolines of stress beneath a tire or track extend into the soil to a depth that is proportional to the width of the tire or track. So, for equal stress at the surface, larger tires or tracks affect the soil to a greater depth than smaller tires or tracks (Soehne, 1958). The stresses at the surface remain equal with increasing tire size when the total vehicle mass increases in proportion to the tire size. Thus, a larger vehicle mass will affect soil to a greater depth than a vehicle of smaller mass with the same stress at the surface (Botta et al., 2002; Berli et al., 2004).

Tractors and other agricultural vehicles have gotten bigger in recent decades (Soane and van Ouwerkerk, 1994a). Such vehicles cause concern over subsoil compaction, which is harder to see and harder to reverse than compaction at the surface (Hakansson, 1994).

Repeated Loadings

When the soil is weak enough, or the stresses great enough for compaction to occur, the impact severity and depth of impact increase with repeated passages of the vehicle (Kirby et al., 1997a). The first pass of a wheel does the most compaction (Cooper et al., 1969), but the effects of repeated wheeling can still be measured after several passes (Bakker and Davis, 1995; Hamza and Anderson, 2005).

Plowpans. Plowpans result from implement action, which can cause both compaction and smearing, depending on the state of the soil during plowing. Unless a tine has a perfectly sharp edge (which, even if it did initially, would soon wear and become rounded), the underside of the rounded tip will exert large compressive forces on the soil. If the soil is very wet, it will smear. If is wet, but not very wet, it will compact. It is known that at about the plastic limit, soil is in its most friable state and thus in the best condition for plowing (Davies et al., 1972; Dexter, 1988).

Animals. We have concentrated above on compaction by agricultural vehicles, but treading by animals also causes compaction and smearing (Willatt and Pullar, 1983; Hamza and Anderson, 2005). The stress exerted by animal hooves can be great, but since the gross mass of the animals is small, compaction by animals is restricted to the surface soil (Hamza and Anderson, 2005). Repeated treading by animals around gateways and watering points can lead to considerable compaction.

Trees. Trees are heavy and exert considerable stress on the soil. The stress is increased by the swaying of the tree in the wind. The dead weight and swaying of trees has been shown to cause considerable compaction (Graecen and Sands, 1980). The greater concern in forest soils, however, is the compaction caused by the heavy vehicles used in forest operations, and the hauling out of the felled trees (Graecen and Sands, 1980).

COMPACTING FOR ROADS, SEED-SOIL CONTACT, ETC.

Sometimes, it is desirable to compact soil – for example, to make a roadway, a dam base, or to provide better seed-soil contact in the seedbed. The considerations discussed previously indicate that to compact soil effectively, it should be moist, but not too wet (or smearing will result with no compaction). Repeated loadings enhance compaction. Compaction for road bases and other purposes has been extensively studied in civil engineering, and most text books describe the classic compaction curve shown in figure 4 (Lambe and Whitman, 1969), which results from repeated loading of test specimens at a range of moisture contents. When the soil is dry, little compaction results from vehicle traffic. When it is very wet, the soil is saturated and again little compaction results. The maximum compaction occurs at an intermediate moisture content, referred to as the optimum moisture content. Those aiming to enhance compaction should aim for this moisture content.

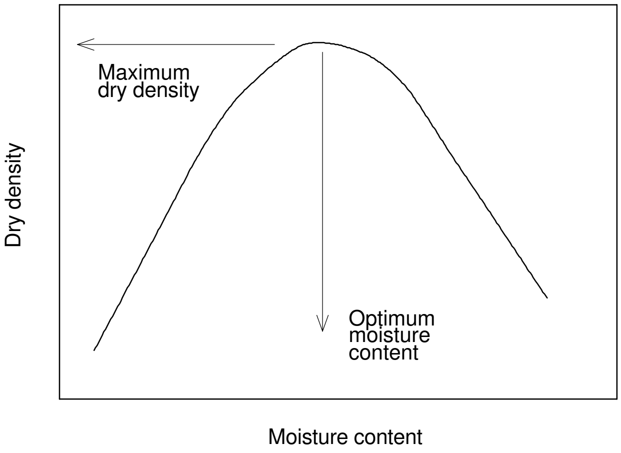

Figure 4. Schematic compaction curve, showing the maximum compaction at the optimum moisture content.

As shown above, repeated loadings lead to greater compaction. When it is desired to compact soil, therefore, repeated loadings are advantageous and compaction equipment often vibrates the soil (Tran and Muro, 2004).

UNDOING IT (FIXES)

Once soil has become compacted, several methods may be employed to reduce or eliminate the compacted soil condition. Processes for reducing the effects of soil compaction vary from those requiring minimal input (natural compaction alleviation) to those that require maximum input (subsoiling). Use of a conservation tillage system that may include components of natural compaction alleviation and subsoiling may also be helpful in reducing the negative effects of soil compaction.

NATURAL COMPACTION ALLEVIATION

Soils that are properly managed may return to a more productive condition with reduced effects of soil compaction, which is gradually dissipated over several years. Two processes that may contribute to this condition are freeze-thaw and shrink-swell cycles. It has been hypothesized that soils that are found in climates with deep freeze-thaw cycles are not subject to extreme soil compaction. The expansion of water when it freezes can raise the soil surface by a significant amount theoretically loosening compacted soil profiles. Another natural process that also could theoretically have some beneficial effects is the shrink-swell process found in smectite clay soils. In the United States, these smectitic soils are mostly found in Vertisols which are present in Texas and Alabama and Mollisols which are present in the central United States (Brady, 1974). These clay soils expand significantly when wet. When dry, large cracks form that may extend downward into the soil for several meters. The continual wetting-drying process could perhaps lead to reduced effects of soil compaction.

Bulk density is not normally reduced by natural compaction alleviation, including the freeze-thaw process (Voorhees and Lindstrom, 1984). Heaving due to frost does not have long-lasting effects; soils tend to quickly consolidate and return to almost the same initial bulk density (Kay et al., 1985). Soil that is compacted by heavy loads seems especially ignorant of the freeze-thaw process as soil compaction is still present after many years of freeze-thaw cycles which penetrate the soil to depths of 40 to 70 cm (Voorhees et al., 1986; Etana and Hakansson, 1994).

Most research points to the gradual improvements in soil compaction caused by natural processes, but little research indicates complete eradication of soil compaction. Vehicle traffic, which penetrates deeply into the soil profile, may cause semi-permanent soil compaction, which will reduce crop yields for many years or even permanently.

CONSERVATION TILLAGE SYSTEMS

In the modern agricultural era, producers have attempted to create a loose, uniform seedbed for planting. Several tillage operations were considered necessary to remove crop residue from the soil surface and reduce the size of clods to optimize the soil-seed contact area. Typically, several passes with agricultural vehicles 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. As much as 70% of a field is reportedly trafficked by vehicle traffic in a conventional tillage system. Compounding the problem is that the first pass of a wheel on loose soil is responsible for about 85% of the total compaction (Cooper et al., 1969). Therefore, a producer using a conventional tillage system could easily traffic 70% of his field to 85% of the maximum compaction limit. Producers who have used conventional tillage systems for decades may have gradually created compacted soil conditions and reduced yields.

Conservation tillage systems, however, do not rely on a loosened soil profile but instead benefit from increased soil moisture commonly found when the soil is not tilled. 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 conservation tillage systems are (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.

Increased soil compaction is often reported when producers switch to a conservation tillage system (Potter and Chichester, 1993). However, increased soil compaction found in conservation tillage systems may only be temporary, may not adversely affect crop yields, and may have increased infiltration and reduced runoff. Conservation tillage systems often have more macropores due to increased biological activity and promote higher rates of infiltration and increased water availability. These macropores 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. Macropores, found in conservation tillage and no-till systems, would also contribute to reduced runoff and sediment losses (Mostaghimi et al., 1988).

Increased soil organic matter, commonly present in conservation tillage systems, may lead to reduced effects of soil compaction (Thomas et al., 1996). Increased organic matter may also lead to an increased amount of water in the soil profile that is available for crop use during the growing season (Hudson, 1994).

Winter cover crops are often used in conservation tillage systems and are particularly effective in increasing the amount of organic matter near the soil surface (fig. 5). The use of cover crops has also contributed to reduced effects of soil compaction, mostly by contributing to increased water infiltration and storage (Raper et al., 2000a, 2000b). In these studies, reduced soil strength (fig. 6) and higher soil moisture contributed towards higher crop yields. Improvements in soil structure and soil moisture have been attributed to cereal grain [rye (*Secale cereale* L.), wheat (*Triticum aestivum* L.*)*, etc.] and legume [crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* Roth), etc.] cover crops (Reeves, 1994). These cover crops have increased soil organic matter mainly due to increased biomass production generated by the cover crop itself and also by increasing yield of the following cash crop.

Figure 5. Researchers examining winter cover crop of rye.

Another positive benefit of cover crops and increased organic matter is that the soil is better able to support vehicle traffic (Ess et al., 1998). 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 to 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.

Because of increased bulk density and the ability to maintain traffic in the same location as previous years, conservation tillage systems may be able to withstand higher compactive forces from vehicle traffic. Forces caused by vehicle traffic will be contained within the elastic soil medium beneath the tires and will not compact the loosened soil material immediately beneath the crop row.

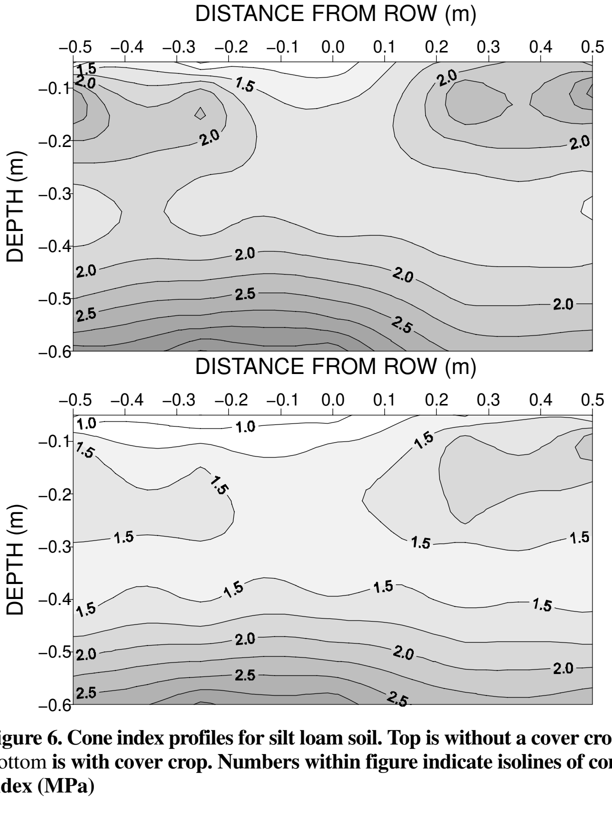

Figure 6. Cone index profiles for silt loam soil. Top is without a cover crop. Bottom **is with cover crop. Numbers within figure indicate isolines of cone index (MPa)**

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. Tillage below depths of 35 cm is referred to as subsoiling (*ASAE Standards*, 1999). Tillage conducted by a narrow tillage tool inserted shallower than this depth is typically referred to as chisel plowing. Although tillage has been performed for several thousand years to loosen the soil surface, subsoiling is a relatively new operation having only been performed since vehicles have excessively compacted the soil with their large mass and frequent traffic. Prior to the 20th century, the ability to till deeper than just a few inches was not possible due to a lack of tractive force, nor was it usually necessary because compaction at these depths was largely caused by repeated traffic of the same large vehicles. In addition, naturally dense subsoils (e.g. fragipans) require such treatment. Currently, subsoiling is practiced on a routine basis throughout the world. Many soils respond positively to subsoiling, with yield improvements normally being found. Tillage tools used for subsoiling vary widely and result in differences in residue remaining on the soil surface, draft force requirements, and belowground soil disruption. However, subsoiling is an expensive operation, which must be done correctly for greatest benefit.

Determining when a soil requires subsoiling requires some measurement of soil compaction. Cone index is the most accepted measure of soil compaction and has been used to determine when roots are restricted and can no longer expand into soil. This term is defined as the force required to insert a standard 30° cone into the soil (*ASAE Standards*, 2004a, 2004b). When values of cone index approach 1.5 to 2 MPa, root growth becomes limited and plants can start suffering the ill effects of soil compaction (Taylor and Gardner, 1963). After subsoiling, however, cone index values as low as 0.5 MPa are commonly found down to the depth of tillage (fig. 7).

It is also important to note that subsoiling should be done at the correct moisture content, or it may do more harm than good. A wet soil will be smeared, creating a plowpan. As noted previously, the plastic limit gives an indication of the ideal state for tilling soil (Dexter, 1988).

The most obvious benefit of subsoiling is to disrupt deep compacted subsoil layers. If soil compaction is excessive in these layers, roots cannot penetrate and are restricted to shallow depths. During times of drought, plants grown in a compacted soil are immediately susceptible as their roots are confined to shallow zones, which do not contain adequate soil moisture. Subsoiling soils with excessive soil compaction provides loosened soil for root growth. The depth of root growth is increased and the plants are better able to withstand periods of drought.

Coupled with the increased root growth is the improved infiltration that usually accompanies subsoiling. Rainfall that previously exceeded infiltration capacity can be stored in the subsoil. The loosened soil provides pathways into the soil for rainfall to move quickly, instead of ponding on the soil surface and eventually evaporating or running off. Larger amounts of soil moisture may then be available to the plant during the growing season when moisture may be limited.

Increased numbers of macropores are often found after subsoiling which contributes to increased infiltration (Xu and Mermoud, 2001). Even though some of these pores will disappear as the soil reconsolidates, many will stay open and provide increased storage of water and oxygen for plant roots. However, it is important that subsequent vehicle traffic be minimized to achieve long lasting effects of subsoiling. Some research has reported that benefits of subsoiling are lost by the second pass of a vehicle tire. This could mean that subsoiling might not benefit a crop if traffic from a primary tillage operation and a planting operation were allowed to stray too close to the subsoiled channels. Maintaining the loosened soil profile and the increased storage capacity for water could be extremely valuable to plant roots during temporary summer droughts.

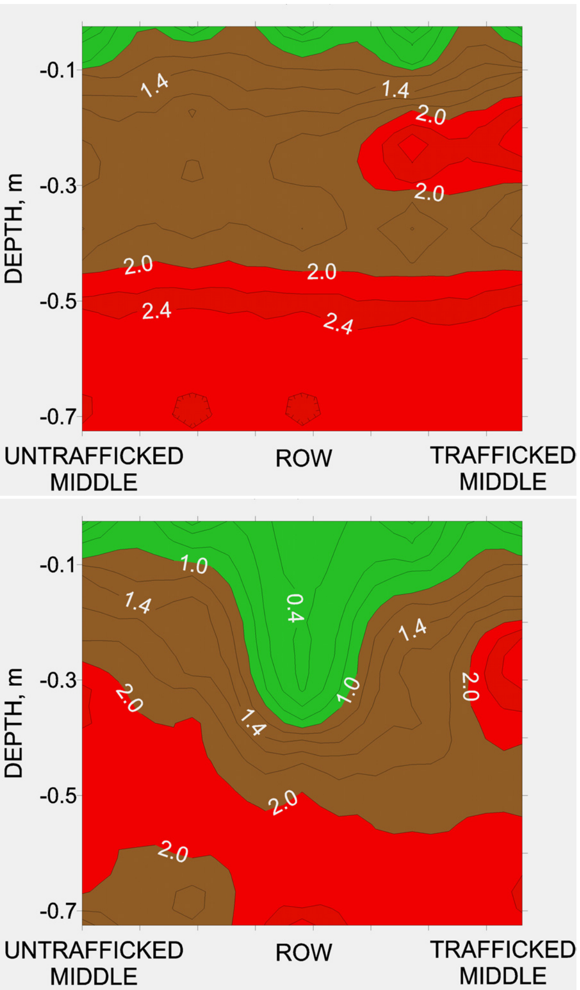

Figure 7. On top is cone index profile (MPa) showing soil that is compacted beneath row. On bottom is cone index profile showing benefit of subsoiling operation beneath row (Raper et al., 1998).

Ultimately, crop yields often improve from subsoiling, although the amount of improvement is difficult to determine as soil type, soil condition, plant species, and climate all have a large effect (figs. 8 and 9). Many soils have shown benefits of being subsoiled, however, their amount of relative benefit may be offset by the expense of performing the operation. Some coarse-textured soils (sandy to loamy), which may compact easily and require minimum tillage forces for subsoiling, show significant yield improvements when subsoiled (Gameda et al., 1994b; Smith, 1995; Sojka et al., 1997).

In some soils where severe compaction is not a problem, subsoiling should not be expected to result in increased crop

Figure 8. Cotton plants growing in soil that was not subsoiled compared to nearby rows that benefited from subsoiling operation.

Figure 9. Grain sorghum growing in middle two rows that was not subsoiled as compared to outside rows that were subsoiled.

yields. Several studies in Mollisols in Midwestern soils have not shown yield increases although soil compaction was temporarily reduced (Gaultney et al., 1982; Evans et al., 1996). Subsoiling may not also result in increased crop yields when irrigation is available (Coates, 1997; Aase et al., 2001; Camp and Sadler, 2002). Increased pore space and rooting is not necessary when water is plentiful.

Even though it is possible to subsoil a field to remove compaction, care should be exercised before this potentially expensive operation is performed. Once soil is loosened by subsoiling it will easily recompact if traffic is applied in the same area. Research indicates that two passes of a tractor in the subsoiled area will cause the soil to return to its previous state prior to subsoiling (Blackwell et al., 1989). If traffic is controlled, however, the benefits of subsoiling can be long-lasting and beneficial for following crops. The overall management of the system should be examined to determine if the soil compaction that is being alleviated by subsoiling is natural or if it is traffic-induced. If it is natural, then subsoiling may have to be performed on an annual basis to give plants the maximum benefit of the operation. However, if a portion of the compaction is machine-induced, adoption of controlled traffic or a cover crop may enable the subsoiling operation to be performed less frequently.

AVOIDING IT (MANAGEMENT)

Prevention of soil compaction may offer the best alternative for reducing its' detrimental effects. Reducing the loads applied to the soil or spreading the loads out over the soil surface may decrease the depth and degree of soil compaction and may allow the soil to simultaneously provide an effective crop growth zone and vehicle support zone. However, another approach may be to completely separate the two zones and adopt a controlled traffic system that restricts vehicle traffic to certain areas of the field.

DECREASED AXLE LOAD

As stated previously, soil compaction near the soil surface is mostly determined by the specific pressure applied by vehicle loads at the surface while the more damaging soil compaction that occurs deeper in the soil profile is mostly controlled by the amount of load (Soehne, 1958). The term 'axle load' was created to define the amount of mass that was applied to the soil for each axle beneath a vehicle. Experiments conducted to evaluate the effect of unequal axle loads determined that soil pressures as deep as 50 cm increased with increased axle load (Taylor et al., 1980). Other experimental studies have found that increased axle load at constant inflation pressure increased soil stresses, soil bulk density at shallow depths, and bulk density at depths near the hardpan (Bailey et al., 1996). Similarly, computer models determined that axle load was also the prime factor in deep soil compaction (Kirby et al., 1997b). These studies point to the need to reduce vehicle mass as a primary 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.

Many field experiments have been conducted worldwide to determine the effect on soil conditions and plant growth of completely covering the soil surface with different axle loads. Most research has determined that axle loads of greater than 10 Mg penetrate the subsoil and result in increased cone index or bulk density measurements (Voorhees et al., 1986; Alakukku and Elonen, 1994; Hammel, 1994; Lowery and Schuler, 1994). Additionally, this research has also determined similar reductions in crop yields from axle loads of greater than 10 Mg, which may persist for several years (Alblas et al., 1994; Gameda et al., 1994a).

Hakansson and Reeder (1994) 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." They also stated that subsoil compaction deeper than 40 cm may be considered permanent even in clay soils with significant freeze-thaw cycles. Using these authors' conclusions, it seems reasonable to restrict axle loads to less than 6 Mg on moist, arable soil as a method of reducing subsoil compaction and keep the resulting compaction in the topsoil region where it can be managed. From the approximate axle loads given in table 1, it may be impossible to limit compaction to near the soil surface when this soil condition is encountered.

SPREAD THE LOAD

Spreading the load out on the soil surface has been an effective method of reducing soil compaction, particularly in the topsoil nearest the soil surface. Increasing the number of

Table 1. Approximate axle loads for agricultural equipment.

Equipment	Axle Load (Mg/axle)
80–kW 2–wheel drive tractor	4
150–kW 2–wheel drive tractor	7.5
240–kW 4–wheel drive tractor	8.5
6–row combine (empty)	10
12–row combine (full)	24
Full single–axle 21–m^3 grain cart	20
Full double dual–axle 38,000–L manure tanker	32 (rear duals) 12 (front duals)

axles under trailers has been offered as a potential solution to reduce axle load on the soil surface and thus reduce the soil-tire interface pressure. However, increased number of axles also means repeated loadings, which can also contribute to increased soil compaction. Increasing tire size may be more favorable as a method of reducing bulk density and cone index than increasing the number of axles (Bedard et al., 1997). However, increased tire size may also increase tire stiffness due to increased number of plys and result in increased soil compaction (Koger et al., 1984). If the crop production system can allow tires with increased width without compacting nearby rows, increased tire width can reduce rutting, cone index, and bulk density due to the ability of the tire to spread the load out on the soil surface (Murosky and Hassan, 1991; Chi and Tessier, 1994).

Dual tires have also been used as a method of spreading the load while maintaining constant axle loads, which may be important for tractive vehicles such as tractors. Taylor et al. (1986, 1989) compared the pressures measured under dual tires to those measured under single tires (fig. 10). The figure shows that dual tires reduced the pressures by about 50% throughout the soil profile to a depth of 50 cm. One negative aspect of using duals, however, is that the soil compaction near the surface is increased in the area under the second tire. Dual tires essentially traffic twice the width of the vehicle track and, depending upon the crop and cropping system, may cause excessive surface compaction.

Rubber tracks have been widely reported to decrease soil pressures as compared to the soil pressures measured beneath tires. Caterpillar (Peoria, Ill.) first introduced rubber tracks in the late 1980s as a method of reducing soil compaction and increasing tractive efficiency of their vehicles. Steel-tracked vehicles have been proven to have higher tractive efficiency than either two-wheel drive or four-wheel drive tractors (Domier et al., 1971; Osborne, 1971) but their use in agriculture has been met with resistance from producers due to the problems associated with speed, vibration, and moving them from field to field. Increased soil pressures and bulk density have also been found for tires as compared to steel and rubber tracks (Taylor and Burt, 1975). However, similar soil pressures have been measured under rubber-tracked and tired vehicles with similar mass in field research (Kirby and Zoz, 1997; Turner et al., 1997). Even though the average ground pressure exerted by the tracked vehicle was smaller due to its increased footprint, the data indicated that rollers, which were similar in magnitude to those measured under tires, exerted substantial peak pressures. Kirby and Zoz (1997) found that stresses measured near the soil surface were similar for both tires and rubber tracks, but at a depth of 35 to 45 cm, the stresses beneath tires were greater than those measured beneath rubber tracks. Dual tires have been found to cause either reduced or increased soil compaction than tracks depending on the inflation pressure maintained in the tires (fig. 11; Abu-Hamdeh et al., 1997).

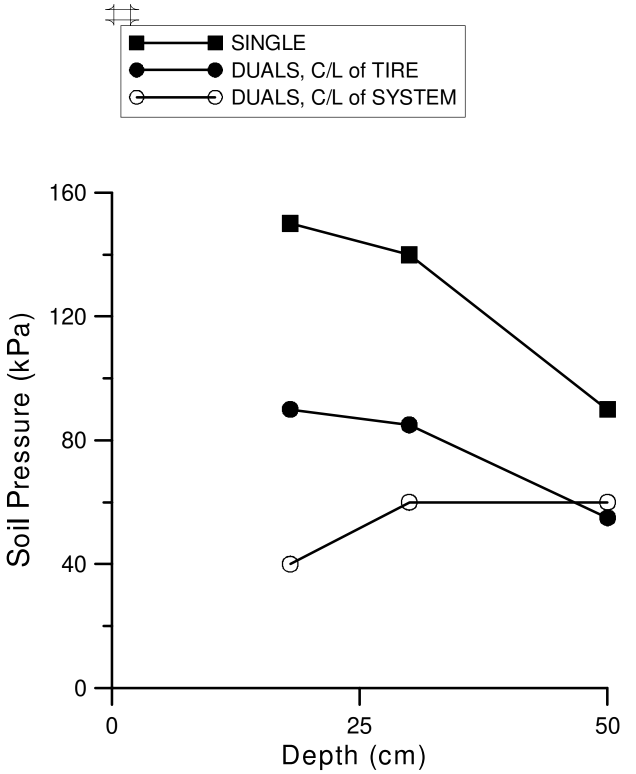

Figure 10. Soil pressures measured beneath single and dual tires (Taylor et al., 1986).

Radial tires are another innovation that has proven to reduce soil compaction and traction. Prior to the early 1960s, bias-play tires were the only option for tractors. The introduction of radial tires offered a realistic alternative that increased the ground contact area thus increasing traction and reducing soil compaction (Thaden, 1962). Initial claims of radial tractor tires included improvements in traction of up to 20% that were proven in controlled soil bin tests (Forrest et al., 1962). Radial tires are even more advantageous as soil firmness improves as is typically found with conservation tillage systems (Taylor et al., 1976).

Maintaining proper tire inflation pressure is imperative when using radial tires. As illustrated in figure 11, the use of correct inflation pressure in radial tires can reduce the soil compaction caused by heavy agricultural vehicles. In soil bin tests on Norfolk sandy loam soils and Decatur clay loam soils, Raper et al. (1995a, 1995b) found 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. 12). Reduced cone index and bulk density measurements (Bailey et al., 1996) were also found in the center of the wheel track when the radial tractor tire was properly inflated.

Another method of spreading the load over the soil surface may involve using another material between the tire/track and the soil as a buffer. In forestry applications, the presence of tree harvesting residue (slash) may reduce the ability of

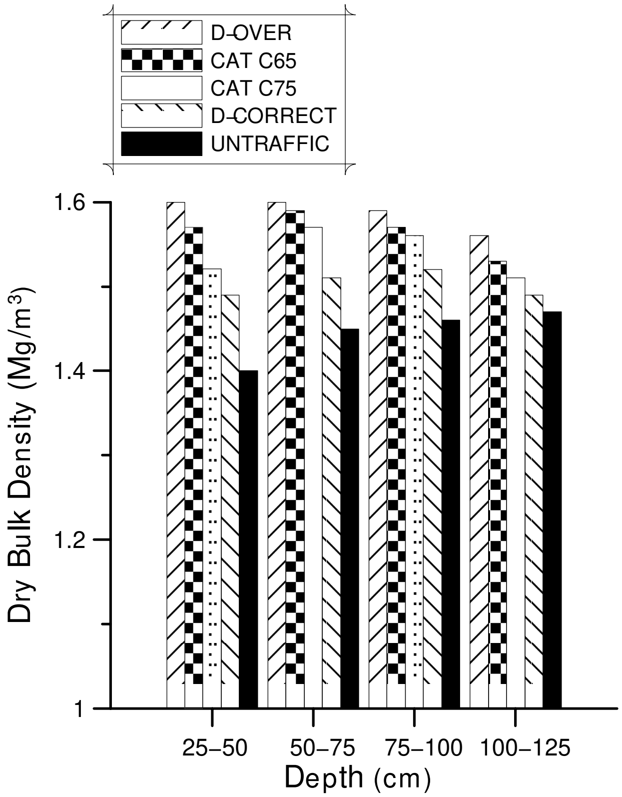

Figure 11. Dry bulk density measured for excessively inflated dual tires (D-over), Caterpillar 65 (C65), Caterpillar 75 (C75), correctly inflated dual tires (D-correct), and untrafficked soil (Abu-Hamdeh et al., 1997).

soil pressures to penetrate the soil, particularly from repeated passes of wheel traffic (Seixas et al., 1995).

CONTROLLED TRAFFIC

Separating the areas used for root growth and the areas used for vehicle traffic is a very useful form of limiting soil compaction. A controlled traffic system was defined by Taylor (1983) 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. Tires and tracks on compacted traffic lanes are also able to increase tractive efficiency and have higher flotation. The crop production zones between lanes are only used for plant growth and are not compacted by vehicle traffic. Soil compaction in the crop growth zone is virtually eliminated except for naturally occurring conditions and those caused by tillage implements.

Development of a controlled traffic system using existing tractors was partially successful and showed increased crop yields and a reduced need for deep tillage (Williford, 1980). Similar research using existing tractors indicated that the effect of subsoiling was found to be longer-lasting in a controlled traffic system (Colwick et al., 1981). Morrison (1985) discussed several options for using normal tractors and harvesting equipment. He found that the most likely wheel spacings would be 1.5, 2.3, or 3.0 m, but dual wheels (common on some tractors) would have to be eliminated and replaced by tandem wheels. The 3.0-m spacing seems to be the most likely wheel spacing that most growers who use controlled traffic are adopting. Harvesters can be easily set to this wheel spacing as can most tractors with the use of additional spacers.

Developing a controlled traffic system using traditional tractors and harvesters begins with ensuring that all equipment covers the same width, or multiples of that width

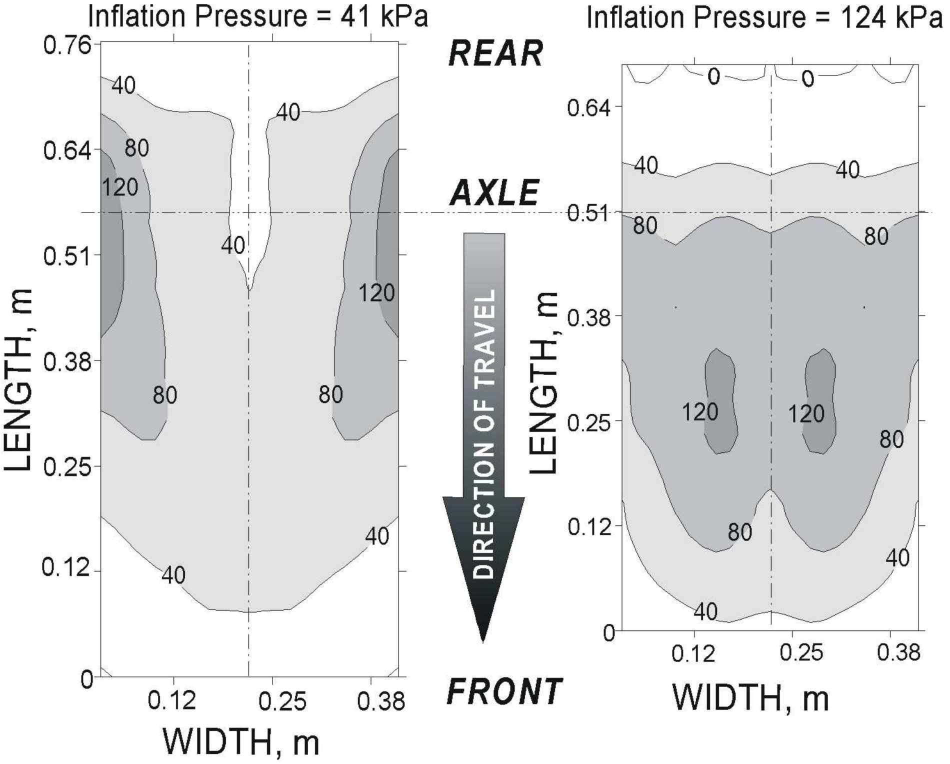

Figure 12. Soil-tire interface pressures for an 18.4 R38 tire. On the left, the tire is correctly inflated (41 kPa) and on the right is excessively inflated (124 kPa).

(Reeder and Smith, 2000). It is usually best to start with the harvester and then match the number of rows with similar widths (or multiples of that width) with planters, drills, sprayers, etc. Additionally, an effort should be made to minimize the number of traffic lanes present within the field and ensure that all vehicles use the established lanes.

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. (1982) developed a gantry machine which spanned 3.3 m for controlled traffic research. Another larger gantry unit with a 6-m wheel spacing (fig. 13) was created at the USDA-ARS National Soil Dynamics Laboratory in Auburn, Alabama (Monroe and Burt, 1989) for controlled traffic research. Reduced values of cone index and bulk density have been found with the use of this gantry in Coastal Plain soils but corn, cotton, and soybean yield response varied depending upon year and rainfall (Reeves et al., 1992; Raper et al., 1994; Torbert and Reeves, 1995). Another potential benefit of the controlled traffic system is the elimination of a requirement for large horsepower tractors for subsoiling, due to the improved soil structure.

Another benefit of a controlled traffic system includes improved traction on soil compacted to create traffic lanes. Rigid soil provides enhanced traction characteristics, which could allow the vehicle to generate more traction and therefore more drawbar power than it would on loose soil (*ASAE Standards*, 2003). Smaller tractors could be used to perform similar tasks due to their improved traction characteristics.

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 to 3 cm precision and are now gaining wide acceptance in Australian and 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 previously compacted soil.

Figure 13. Wide-frame tractive vehicle used for controlled traffic research at the USDA-ARS National Soil Dynamics Laboratory in Auburn, Alabama.

AN HISTORICAL NOTE, A QUESTION, AND A PARTIAL ANSWER

What we have described in this article, while relying for its detail on much modern research, has been known in general outline for many a long year. Indeed, much of it has been published in literature aimed at farmers. Thus, Davies, Finney, and Eagle wrote in 1972 in a handbook aimed at farmers (Davies et al., 1972):

> "Increasing tractor and implement weight and its effect on soil structure and crop growth has caused concern over most of the years of this century. The arrival of rubber tires increased concern since ballasting of a basically heavy tractor became necessary to get traction. The problem of soil smearing by a slipping rubber tire was recognized.
>
> Adverse effects of traffic were noted long before the advent of tractors. Jethro Tull in the 18th century noted that people who overworked soil in a moist state made it like 'a highway,' through frequent treading by horses. By the end of the 19th century, subsoil tines attached to ploughs were used to break pans caused by horses and plough soles in the furrow bottom. The effect on crop yields of traffic at ordinary levels is difficult to show experimentally, although there are many well-documented case studies of severe effects of traffic on commercial farm crops where, possibly because of a difficult season or mismanagement, structure has been damaged.
>
> The effect of traffic on the soil has been shown to be increased bulk density, increased shear strength, reduced porosity and reduced air and water permeability."

This introduction makes clear that the broad effects have been known since at least the 18th Century, and have moved beyond research literature into the domain of practical farmer advice. Indeed, there are hints of soil management and the importance of the correct soil moisture content at sowing in FitzHerbert's "Boke of Husbandry" in 1523, and also in the Roman descriptions of agriculture (Colemmla, in De Re Rustica Book II article 4, for example writes "Let us, then, above all, follow a middle course in ploughing our lands, that they may neither be entirely wanting in dampness nor immoderately wet; for too much moisture, as I have said, makes them sticky and muddy, while those that are parched with drought cannot be properly loosened" in http://penelope.uchicago.edu/Thayer/E/Roman/T exts/Columella/de_Re_Rustica/2*.html). Hall (1909) noted that in spring cultivation after the wet winter, "The drying of the surface soil ... is of the greatest possible importance in obtaining a tilth." Tillage and compaction, of course, are not the same, but we have pointed out the similarity of the soil moisture considerations and that wet soil smeared by plowing is probably also compacted by the horse or oxen pulling the plough. As reviewed by Soane and van Ouwerkerk (1994b), compaction concerns have accompanied the growth in use and size of tractors ever since the introduction of steam engines, and particularly throughout the 20th Century with the rise of modern tractors.

The rest of the Davis, Finney, and Eagle's book provides greater detail, including the problems of random traffic, and offers much practical advice on compaction management (and other soil management). Other literature aimed at farmers also carries excellent summaries of compaction knowledge, and practical advice for framers to follow (eg., SOILPAK in Australia; many ARS web sites in the United States).

As we pointed out in the introduction, there is an extensive literature on research into compaction, continuing up to the present day. By and large, this literature confirms and adds detail to Davies et al. (1972) and the other extension literature, but does not add profound new insight.

Given this history of knowledge, the excellent summary by Davies et al. (1972) and those in other extension literature, it is pertinent to ask: why is research into compaction still being conducted – what are the important new issues still requiring answers? Briefly, we think that there are various reasons for continuing interest in compaction research.

- Farmers can't always follow the obvious compaction advice (sometimes the crop must be sown or harvested irrespective of the state of the soil, and compaction is sometimes less important than equipment productivity), van den Akker et al. (2003) lament the fact that the advice about compaction is well known and yet unheeded. They conclude that compaction remains important, and new solutions are still needed.
- Compaction can usually be counteracted with other management (irrigation, fertilization, plowing) (Hamza and Anderson, 2005), and there remains a need to specify the best overall management systems particularly in relation to bed farming/permanent lanes.
- New equipment, tires, etc., require confirmation of the best conditions of use including the impact on compaction.
- Reduced tillage systems may not offer opportunities for routine compaction disruption as was once commonly conducted with moldboard plowing or full-width subsoiling operations.
- Compaction (and tillage) does not always lead to the simple, measurable effects. Hydraulic conductivity shows considerable variability and changes, while measurable, may not be significant (Boizard et al., 2000). Although conductivity may be reduced by compaction, the impact on soil water status also depends on various other factors (boundary potentials driving flow, soil layering, etc) and the changes due to compaction may be difficult to measure (Horton et al., 1994).
- Compaction may not always be important and the significance is sometimes disputed [Schafer-Landefeld et al. (2004); discussed by Ehlers et al. (2005), who disputed their interpretation on the grounds that, amongst other things, they hadn't properly accounted for the influence of moisture content; and the reply by Koch et al. (2005), refuting this], so there may remain a need to identify the range of actual conditions in which compaction is important.
- In scheduling operations in large areas – in forestry or pipeline laying, for example – mapping of compaction likelihood by season will be important, so that operations may be confined to less susceptible soils during wet periods. Jones et al. (2003) developed a preliminary map of the susceptibility of European soils to compaction, aimed at assisting in the planning of field operations. We agree with van den Akker et al. (2003) that this is an area for new work.
- Although there have been some economic appraisals of the cost of compaction [eg., the three papers in the section on economics of compaction in Soane and van Ouwerkerk (1994a)], few studies include economics. A full study of the economic decision-making in farming would reveal the importance of compaction relative to other factors, and perhaps lead to better targeted advice. One of us (MK) was once told by the manager of a large, commercial cotton farm that a move to permanent beds (which had the happy consequence of reducing compaction in the beds) was done on the basis of an economic appraisal which revealed that fuel saving in a bed system would increase profitability more than any other factor. We therefore agree with Soane and van Ouwerkerk's (1994b) call for greater efforts on whole farm economics.

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