Tires, Traction and Compaction

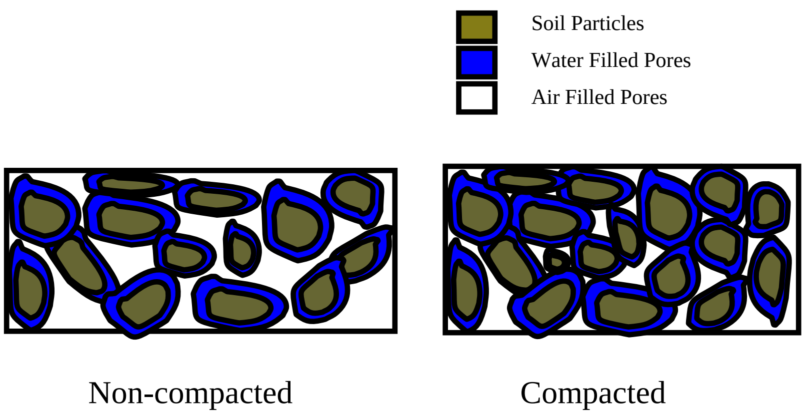
Jodi DeJong-Hughes, University of Minnesota Extension

1. What is Compaction?

Soil compaction occurs when soil particles are pressed together, reducing pore space between them (Figure 1). Heavily compacted soils contain few large pores, less total pore volume and consequently a greater density. A compacted soil has a reduced rate of both water infiltration and drainage. This happens because large pores are more effective in moving water downward through the soil than smaller pores.

With increasing farm size, more acres need to be covered each day to conduct field operations in a timely manner. The width and weight of field equipment is increasing and so is the horsepower of the tractors needed to pull them. The weight of tractors has increased from less than 3 tons in the 1940's to approximately 18 tons today for the big four-wheel-drive units. Wheel traffic is without a doubt the major cause of soil compaction.

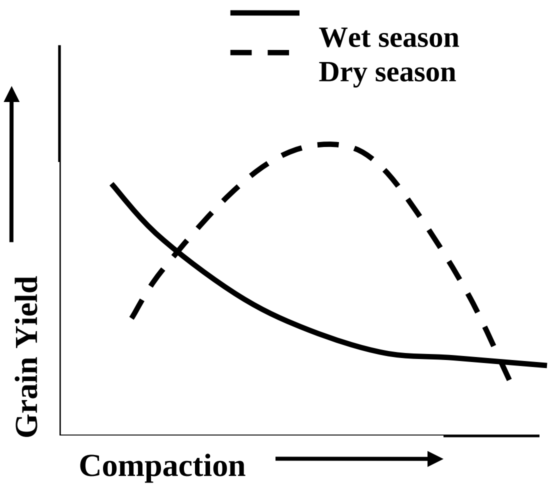
Figure 1. Effects of compaction on pore space. Figure created by Neil Hansen, UMN, 2003.



Soil compaction can have both desirable and undesirable effects on plant growth. Research from North America and Europe indicates that crops respond to soil compaction as shown in Figure 2. In a dry year, at very low bulk densities, yields gradually increase with an increase in soil compaction. A slightly compacted soil can speed up the rate of seed germination because it promotes good seed to soil contact. This is why corn planters have been designed specifically to provide moderate compaction with planter mounted packer wheels that follow seed placement.

As soil compaction increases beyond optimum, yields begin to decline. In dry years, soil compaction can lead to stunted, drought stressed plants due to decreased root growth. Without timely rains and well-placed fertilizers, yield reductions will occur.

Figure 2: Effects of weather on crop yield response to compaction level (8).



With wet weather, yields are decreased with any increase in compaction. Soil compaction in wet years decreases soil aeration resulting in increased denitrification. There can also be increased risk of root diseases. All of these factors result in added stress to the crop and, ultimately, yield loss.

This publication will look at the effects of soil compaction on crop growth and yield, the potential for alleviating compaction, and management for minimizing soil compaction.

2. Effects from Compaction

- ***a. Soil Structure***
- ***b. Nutrient Uptake***
- ***c. Crop Emergence and Stand***
- ***d. Crop Growth and Development***
- ***e. Crop Yield***
- ***f. Iron Deficiency Chlorosis***
- ***g. Overall Crop Energy***

2a. Soil Structure

Under the influence of microbial activity, soil particles bind into generally stable units that are called structure. Heavy equipment and tillage implements can damage and reduce soil structure. Structure is an important defense against soil compaction. Without good structure, individual soil particles are more susceptible to compaction from external pressure increasing bulk density and decreasing pore space. Heavily trafficked soils retain moisture longer, recharge more slowly, and are slower to warm up compared to less compacted soils.

In the Midwest, using deeper tillage implements in combination with disks, shanks and harrows destroys soil structure and loosens the soil to a depth of 10-16 inches. While this temporarily aerates the soil and lowers the bulk density, seed to soil and root to soil contact can be reduced. The air that has been introduced into the soil does not have any load bearing capacity and the soil can be easily compacted after tillage. Examples of slower germination and growth in wheel tracks have become more common.

When structure and pore space are reduced there is less air and moisture in the soil. This condition negatively influences all phases of crop production including seed germination; seedling emergence; root growth; and nutrient and water uptake.

2b. Nutrient Uptake

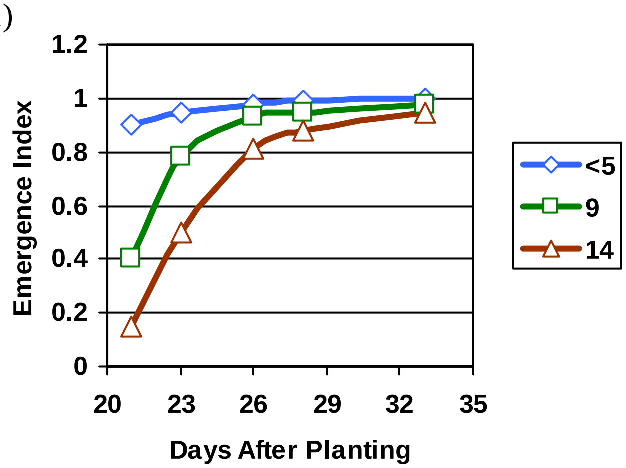
Soil compaction increases soil density. Roots are less able to penetrate the soil and are generally shallow and malformed. Since their growth is restricted they are less able to exploit the soil for nutrients and moisture. Nitrogen and potassium deficiencies are the most common. This leads to additional fertilizer requirement and increases production costs.

Adverse effects of compaction can be reduced by applying fertilizer in ways that improve plant root access. This may include split application of nitrogen or band application of phosphorus and potassium.

2c. Crop Emergence and Stand

Research has shown that increased vehicle traffic delays seedling emergence and that the emergence rate is more variable (Figure 3). While crop emergence from compacted soil may catch up to emergence from non-compacted soil, plants are at a higher risk for disease, predation, and moisture shortage.

Figure 3. The effect of different degrees of compaction (axle loads) on plant emergence (11)



Researchers in Pennsylvania (7) compared three levels of annual compaction; 1.) soil with no compaction, 2.) compaction from road tires inflated to 100 psi, and 3.) compaction from flotation tires inflated to 36 psi. They measured corn population, plant height and yield. The non-compacted plots had a higher plant population than the trafficked plots in 2 out of 4 years. Road tires resulted in lower plant counts than flotation tires (Table 1) due in part to the road tires creating ruts across the field and a greater surface unevenness after the compaction, resulting in poorer seeding depth control. The study concluded that the compaction created from the higher psi decreased plant population versus no compaction.

Table 1. Effects of soil compaction on plant populations (7).

	Plant Populations per Acre*			
Treatment	**2002**	**2003**	**2004**	**2005**
No Compaction	17,800 a	22,270 abc	26,720 ab	26,320 a
Annual Flotation Tire Compaction	15,390 b	22,270 abc	26,320 b	23,480 c
Annual Road Tire Compaction	12,960 c	21,460 bc	25,100 c	23,080 c

*Values within a column followed by the same letter are not significantly different at $p > 0.05$.

2d. Crop Growth and Root Development

Soil compaction can influence plant height by preventing normal root development. This is most detrimental if it is shallow compaction (6-8 inches). If timely rains do not soften the compacted layers so roots can penetrate the soil, plants will be stunted, have fewer fine roots, and less overall root mass. Corn is most sensitive because it is one of the taller crops. By the end of the season, corn may be 6 inches to 4 feet shorter on compacted soil than on non-compacted soil (Figure 4).

Figure 4. The effect of different degrees of compaction (axle loads) on plant height (11).

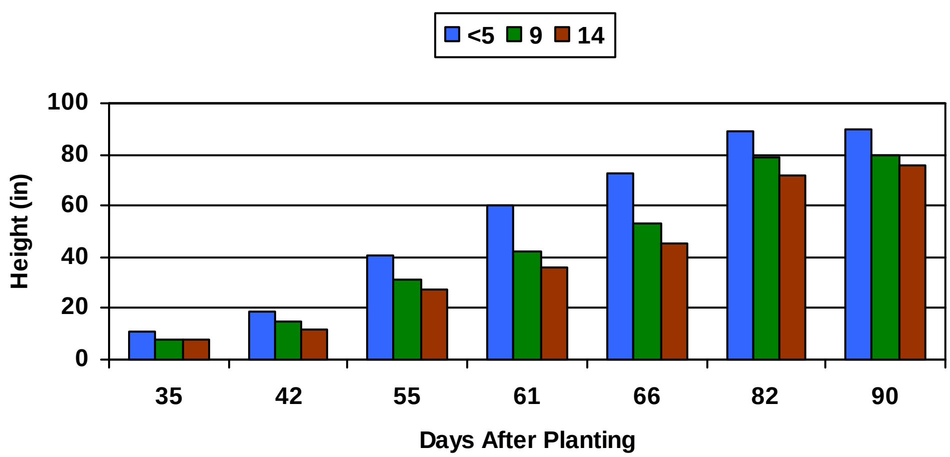


Photo 2 shows a tillage pan that formed due to fall moldboard plowing when soil conditions were too wet. Notice the shallow rooting system that can lead to moisture stress, nutrient deficiencies, and lodgings. While the current year's crop will be affected, it is unknown how long this layer will persist. This is a smectite clay, which is evident by the deep crack on the left side of the photo. The cracking of the clay soil and adequate moisture will lessen the severity of the tillage pan.

Photo 2. A tillage pan located at 6 inches in the soil profile. Photo courtesy of Jodi DeJong-Hughes, University of Minnesota Extension.

In Sidhu's study (7), corn height was affected by soil compaction 6 weeks after planting (WAP) and followed through to harvest (Table 2). Annual road tire compaction reduced plant height by 21% at 6 WAP and 11% at harvest compared to the control while height on flotation tire plots was statistically the same as the non-compacted corn height.

Table 2. Effects of soil compaction on corn height (7).

	2004 Plant Height (inches)*	
Treatment	**6 WAP**	**At Harvest**
No Compaction	28.8 a	114.3 ab
Annual Flotation Tire Compaction	26.4 ab	108.7 abc
Annual Road Tire Compaction	22.5 c	102.4 c

*Values within a column followed by the same letter are not significantly different at p > 0.05.
WAP = Weeks after planting

2e. Crop Yield
Crop yields are reduced when soil compaction decreases crop emergence, crop growth, and nutrient uptake. Some researchers estimate soil compaction can reduce yield as much as 60%. The ranges in yield effects are broad because the outcome of compaction is variable and due to many factors, nor are compaction effects consistent across the field.

Sidhu's study (7) found significant yield reductions with the annual road tire compaction compared to the control in 3 of the 4 years. However, yield differences between flotation tires and the control were not significant in 3 of the 4 years. This may be due to the corn plant being able to compensate for fewer plants per acre with larger ears. They observed that compaction effects on yield are greatest when the crop is under stress, such as from drought or an excessively wet growing season.

Krmenec (5) found that differences in stand count affected final yield in trafficked versus non-trafficked fields. He noted that wheel traffic plots had had a higher number of ears produced; however, the ears were smaller than the ears from the non-compacted plots (Photo 3). The relationship between final yield and wheel traffic was blurred by the corn plant's ability to produce larger ears where plant population was reduced.

Photo 3. Harvest ears from untrafficked row (left) and heavily-trafficked row (right) (5).

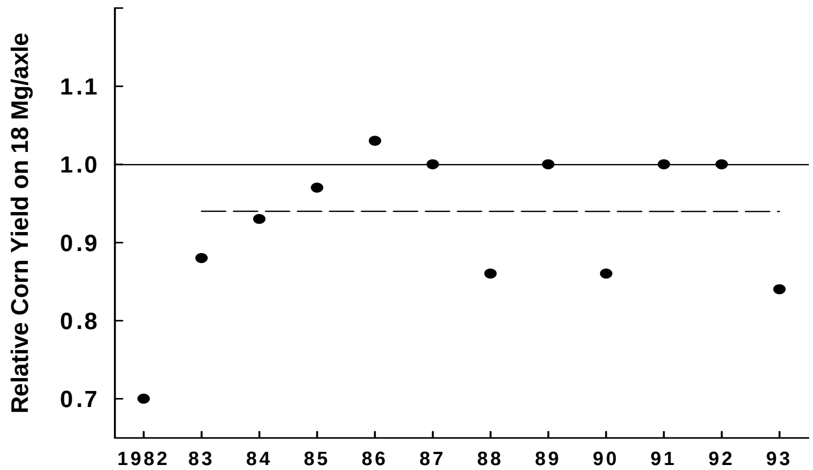
At Purdue University (5), researchers observed stand count reductions of 20 to 30% in the compacted plots. They also measured plant height decreases of one-third to one-half and yield reductions of about 19% compared to non-compacted plots. Corn yields were 160 bushels per acre in non-compacted soil compared to only 130 bushels in compacted plots.

Research studies conducted in northern latitudes show that the effect of severe subsoil compaction may affect crop yields for years. Research results from Lamberton and Waseca, Minnesota; Uppsala, Sweden; and Quebec, Canada (9), show a similar trend of initially lower yields following compaction with axle loads of 10 tons or more. The effect decreased over time, and yields on compacted soil approach the yields on non-packed soil after two to seven years, depending on the soil and climate. Soils higher in clay content had a slower recovery to the effect of compaction.

While these studies show a gradual, natural alleviation of subsoil compaction, the data from Waseca (9) suggests that there is sufficient "residual" subsoil compaction to reduce crop yields in years where there are environmental stresses. Figure 5 shows that corn yields were back to normal within 5 years after the compaction was created. However, in 1988, 1990, and 1993 yields were reduced. In 1988, growing season precipitation was the lowest on record, while in 1990 and 1993, the region received above average rainfall (167% and 175% of the long-term average).

This study illustrates that a one-time compaction event can lead to reduced crop yields 12 years later. Under normal farming operations, heavy equipment is used every year. Thus, subsoil compaction resulting from farming practices may be a long-term issue.

Figure 5. Corn yields over 12 years with a one-time soil compaction of 20 ton/axle relative to non-compacted plots (9).



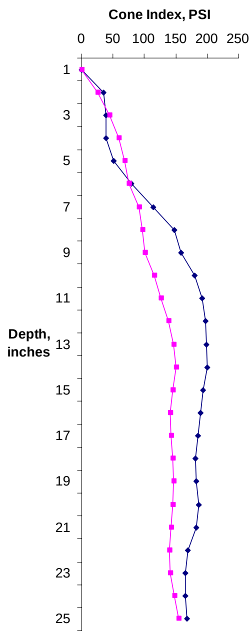
2f. Iron Deficiency Chlorosis

Most effects of compaction are detrimental to plant growth; however there are a few exceptions. Slightly compacted soils in a dry year can increase crop yield as discussed at the beginning of this chapter. Another exception is the case of iron deficiency in soybeans.

Iron deficiency chlorosis (IDC) has become an increasing problem in the Western half of Minnesota and the Eastern quarter of North Dakota. IDC is induced by a combination of factors such as high pH, salts, and calcium carbonate levels. However, it has been observed that wheel tracks running through an area affected by IDC will have green healthy soybeans (Photo 4). Penetrometer readings in the green wheel tracks show an increased bulk density in the top 7-18 inches of soil versus the yellow, chlorotic areas (Figure 6). Decreased pore size in the wheel tracks lead to decreased aeration in the soil, which increases denitrification. In addition, the compacted wheel tracks tend to shed water and have less total water than less-compacted soil between the tracks. This decreases bicarbonate solubility when soils are wet in the wheel tracks, also helping to decrease chlorosis. While compaction is usually a detriment to most Minnesota crops, it can be a benefit to soybeans grown in areas prone to IDC in wet years, although this practice is typically not promoted.

Photo 4_. Green soybeans in the wheel tracks of an area of a soybean field affected by IDC. Photo courtesy of Jodi DeJong-Hughes, University of Minnesota Extension.

Figure 6. Cone index by depth for trafficked soil (blue) versus non-trafficked soil (pink). Provided by George Rehm, University of Minnesota.



When fields show IDC symptoms early in the year, one of two things can happen. One is that as the field dries, water is pulled into the small pored tracks through capillary action, making the tracks moister than between tracked areas. The result is more chlorotic wheel tracks than the between tracked areas (personal communication, Franzen, 2007). However, a majority of the time the wheel tracks stay green throughout the growing season. Whether wheel tracks turn chlorotic or remain green is often the consequence of varietal tolerance to regional IDC soil factors.

Generally, the most effective management for IDC is variety selection. Additionally, there has been success with planting a companion crop, such as oats, to remove excess nitrogen.

2g. Overall Crop Energy
A compacted soil requires more force and energy to accomplish tillage operations. In an experiment in Illinois (3), the energy requirements to prepare a seedbed were measured in a compacted and non-compacted soil. The compacted soil caused a 10 to 16 fold increase in energy required at low speeds and a 4 to 8 fold increase at high speeds. The draft from the narrow chisel increased from 70 pounds in non-compacted soil to 350 pounds in a compacted soil.

3. Management for Reducing Soil Compaction

- ***a. Controlled Traffic***
- ***b. Axle Load and Tire Inflation Pressure***
- ***c. Tracks versus Tires***

While large, heavy machinery is often blamed for soil compaction problems, it also offers opportunity to minimize compaction. Larger capacity machinery means fewer wheel tracks across the field because of wider working width. Approximately 80% of the compaction happens on the first pass. Subsequent passes cause additional, but progressively less, compaction. Based on this concept, if wheel track spacing can be standardized among different pieces of equipment, soil compaction problems can be confined to certain traffic patterns and not throughout the entire field.

3a. Controlled Traffic
Compaction is managed, not eliminated. Controlled traffic is a method to manage soil compaction. All heavy traffic is confined to specific lanes through the crop, year after year. The lanes become compacted and the soil between the lanes is never driven on. Controlled traffic improves timeliness of planting, spraying, and harvesting while minimizing potential yield losses from compaction. Controlled traffic also results in beneficial compaction because the compacted soil under wheel tracks provide better flotation and improves traction when fields are wet.

Converting machinery to controlled traffic is not a simple change, but rather a transition that can take several years to complete (Photo 5). Therefore, consider controlled traffic in all major machinery buying decisions. Tire selection is very important with controlled traffic because minimizing the amount of area compacted is crucial; therefore, taller and narrower tires must be used.

Photo 5. The tractor and grain cart have single tires set on 10 foot centers, matching the combine. Photo courtesy of CSRIS, Australia.

If controlling all wheel traffic is not feasible, control the heaviest equipment like the grain cart. To reduce wheel traffic across the field, grain carts should use the previous combine tracks when possible. For example, after unloading the combine on-the-go, the grain cart should continue to the end of the field and take the headlands back to the field entrance. At all costs, avoid driving equipment across the field at a diagonal.

3b. Axle Load and Tire Inflation Pressure

When we think about compaction potential many think of larger heavier equipment such as combines, grain carts and liquid manure tankers. While a majority of tractors weigh less than 10 tons per axle, the newer 4WD tractors can weigh almost as much as a loaded combine (Table 3). Combines and grain carts, whether equipped with tracks or tires, can create compaction as deep as 3 feet. Keep axle loads under 10 tons to localize compaction in the top 6-10 inches.

Table 3. Approximate axle loads for field equipment. Source: Jodi DeJong-Hughes, University of Minnesota Extension, 2003.

Equipment Axle Load	(Tons/axle)
Slurry tanker, 4,200 gal.	10-12
Slurry tanker, 7,200 gal.	17-18
Class 9 combine, 590 hp, 360 bu capacity	20
12-row combine, full with head	24
Grain cart, 720 bu., full, 1 axle	22
Grain cart, 1,200 bu., 1 axle	35-40
Terra-Gator, rear axle	12-18
4WD Tractor, 200 HP, front axle	7.5
4WD Tractor, 325 HP, front axle	13
4WD Tractor, 530 hp, front axle	18

Total axle load, as well as contact pressure between the tire and soil, affects subsoil compaction. Historically, as equipment weight increases, tire size also increases. This avoids drastic increases in contact pressure (pounds per square inch (psi)) by the tire on the soil surface.

Tractor experts agree there is no single, simpler way to improve tractor efficiency than to use the proper tire inflation pressure (6). Proper tire inflation not only improves tractor efficiency but can reduce the intensity of the compaction from the tires. The table below lists the proper tire inflation per axle load and tire size. When duals or triples are added to a tractor it reduces the carrying load on each tire, thereby reducing the necessary tire inflation rate. This also decreases the depth and intensity of the compaction.

Table 4. Goodyear radial tire inflation pressures based on tire size and loads (www.goodyear.com).

Maximum Speed - 30 MPH										
Tire Size	**Inflation (psi)**	**6**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**
	Symbol						*****			******
16.9R28	Load Index						129			136
	SINGLE (LBS.)	NR	2910	3200	3520	3740	4080	4300	4540	4940
	DUAL (LBS.)	1890	2560	2820	3100	3290	3590	3780	4000	4350
	TRIPLE (LBS.)	1760	2390	2620	2890	3070	3350	3530	3720	4050
16.9R38	Load Index									
	SINGLE (LBS.)	NR	3300	3740	4080	4400	4680	4940	5360	5680
	DUAL (LBS.)	2170	2900	3290	3590	3870	4120	4350	4720	5000
	TRIPLE (LBS.)	2030	2710	3070	3350	3610	3840	4050	4400	4660
18.4R30	Load Index									
	SINGLE (LBS.)	NR	3520	3960	4300	4680	4940	5360	5680	5840
	DUAL (LBS.)	2290	3100	3480	3780	4120	4350	4720	5000	5140
	TRIPLE (LBS.)	2130	2890	3250	3530	3840	4050	4400	4660	4790
18.4R38	Load Index									
	SINGLE (LBS.)	NR	3960	4400	4800	5200	5680	6000	6400	6600
	DUAL (LBS.)	2640	2480	3870	4220	4580	5000	5280	5630	5810
	TRIPLE (LBS.)	2460	3250	3610	3940	4260	4660	4920	5250	5410

Table 4 illustrates the proper tire inflation for the axle load. For a tractor with single tires and an axle weight of 5,840 pounds, the proper tire inflation is 24 psi. When duals are placed on the tractor the proper inflation is reduced to 10 psi. Triples will further reduce the proper psi to 6.

3c. Tracks versus Tires

Any equipment, whether it has tracks or tires, can create compaction. The question is "Which one creates the least amount of compaction"? The answer: "It depends".

<u>Tractors</u>

A parked tracked tractor exerts a ground pressure of approximately 4-8 psi depending on track width, length, and tractor weight. This psi changes with the positioning of mid-wheel rollers, spring stiffness at attachment points, track stiffness, dynamic weight transfer when under drawbar load, etc (Photo 6).

Photo 6. A tracked tractor. Photo by Jodi DeJong-Hughes, University of Minnesota Extension.

Radial tires exert a pressure one to two pounds higher than their proper inflation pressure. For example, if a radial tire is inflated to 6 psi, the tire exerts a pressure of 7-8 psi on the soil. This pressure is also dependent on lug size, tire stiffness, and drawbar load. Bias-ply tires inflated to only 6-8 psi cannot operate efficiently and easily wear-out with such low tire pressure; consequently they have to be inflated to 20-25 psi. To keep soil compaction in the plow zone, maintain radial tire pressures around 10 psi. Depending on tire size, you may have to add duals to achieve this goal. You can go to the internet or your local tire dealer to find the proper inflation pressure for your tires.

Iowa research has shown that small tractors equipped with either tracks or radial tires create compaction in the top 5-8 inches, however, compaction effects were negligible below that depth.

Table 5 shows the correlation between tire inflation pressures and soil compaction found in a study conducted by Ohio State University (1). The compaction effect was measured to a depth of 20 inches, on a silty loam soil (the tires were approximately 28” wide) for four different scenarios. A John Deere 8870 4WD tractor with 710/70R38 duals correctly inflated to 6 and 7 psi (front and rear) and the same tractor with tires over inflated to 24 psi were compared to a Cat Challenger 65 with 24" rubber tracks and a Cat Challenger 75 with 36" rubber tracks. In terms of soil physical properties the tractor with correctly inflated tires ranked as best, followed very closely by the 36" tracks and 24" tracks. The tractor with over inflated tires caused the most compaction. The relative rankings were the same for the vehicles with no load and a towed load (forty foot field cultivator).

Table 5. Soil compaction of four-wheel drive and tracked tractors under various draft loads.

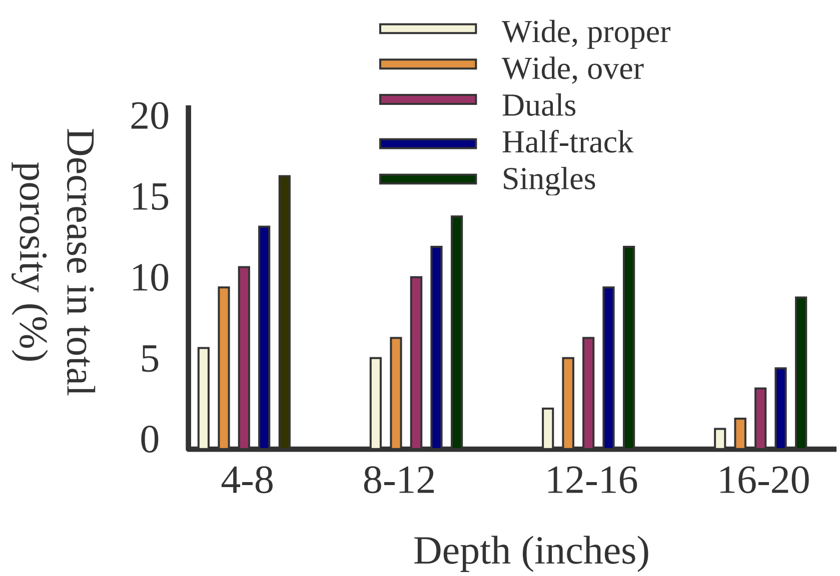
Depth (inches)	Duals with properly inflated tires	Duals with over inflated tires	24" Tracks	36" Tracks
4 - 8	51.9	87.7	78.2	62.3
8 - 12	42.2	73.9	65.4	46.8
12 - 16	32.4	72.9	49.5	38.4
16 - 20	10.9	35.5	26.2	20.7

<u>Combines</u>

What effect do tracks have on subsurface compaction when used in conjunction with heavy field equipment, such as grain carts or combines? Whether the equipment uses tracks or tires, the total axle load is nearly the same. Tracks will improve traction and ride-ability in the field, but a 25-ton per axle grain cart will still create subsurface compaction whether it has tracks or tires.

Another Ohio research project (2) tested a 1200-bu grain cart against a John Deere 9600 combine with different tire/track arrangements. The grain cart with 35 psi dual tires, by far caused the worst compaction. Next in order (worst to least compaction) were the combine with: single 30.5 L32 tires at 34 psi; experimental half-track with an average psi of 10; dual 18.4 R38 at 26 psi; wide 68x50.0-32 overinflated at 24 psi; and the same wide tires at the correct pressure of 15 psi (Figure 7). Note that the half-track had an average calculated pressure on the soil of about 10 psi; but it gave results that appear to make it equal to a tire with about 26 to 30 psi. This is mainly due to the downward pressures exerted from the guide wheels. The researchers hypothesized that the lower the inflation pressure; the better it is for soil porosity.

Figure 7. Decrease in soil porosity by depth with different soil pressure (2).



Grain Carts and Liquid Manure Spreaders

Like combines, grain carts and liquid manure spreader's overall carrying capacity is enormous and axle loads can be as high as 40 tons. Previously, heavy equipment used bias ply tires that need very high inflation pressures to operate effectively.

The tire industry has recently designed radial tires to replace bias ply tires for the larger equipment. This has helped reduce tire pressures to almost half the inflation rate of bias ply tires. Liquid manure spreader manufactures have been adding more axles as the tank load increases, thereby reducing load per axle

Effect on Roadway Pavement

Another rarely mentioned aspect of equipment load is the effect axle load has on road stability. The following table compares the stress on pavement created by a variety of heavy farm vehicles. The number of passes to failure indicates that some vehicle types shorten the life of road pavement with significantly fewer passes.

Table 7. The effect of different axle loads on pavement wear (Iowa Department of Transportation).

TYPE	Axles	# Passes to Failure 6" PCC*	# Passes to Failure 7" PCC*
5-Axle Tractor-Semitrailer 80,000 lbs.	1 Single/2 Tandems	12,000	135,000
7-Axle Tractor-Semitrailer 96,000 lbs.	1 Single/2 Tandems	78,000	175,000
Grain Cart – 900 bu. 58,000 lbs. (20% on tow vehicle)	Tandem	200	6,000
Grain Cart – 875 bu. 57,000 lbs. (20% on tow vehicle)	Single	<10	<30
Grain Cart – 650 bu. 42,000 lbs. (20% on tow vehicle)	Single	<30	270
Grain Wagon – 775 bu. 49,000 lbs.	2 Singles	1,000	60,000
2 Grain Wagons – 450 31,000 lbs. each	4 Singles	106,000	239,000
Combine – Empty	2 Singles (1 tire on pavement)		
27,500 lbs. w/o corn head	18,000 front/9,500 rear	3,790,000	8,468,000
32,000 lbs. w/corn head	26,000 front/6,000 rear	887,000	1,980,000
Combine – w/240 bu.	2 Singles (1 tire on pavement)		
41,000 lbs. w/o corn head	27,500 front/13,500 rear	712,000	1,591,000
46,000 lbs. w/corn head	36,000 front/10,000 rear	100,000	456,000
Large Row Crop Tractor 18,000 lbs.	2 Singles 11,000/front 7,000 rear	1,525,000	3,410,000
Liquid Manure Tanks 7,500 gallon – 71,000 lbs.	2 Tandems 1 Tandem	<10 <10	<30 <30

*PCC – Portland Cement Concrete
Note – Structurally equivalent asphalt concrete pavements have similar impacts.

Notice that the loaded 875 bushel grain cart can make the pavement unstable in less than 30 trips. If the same load was transferred to a 7-axle semi truck, it would take 175,000 passes for pavement failure. If this is what is happening to the roads, imagine what is happening to our soils.

4. Summary

The best way to manage soil compaction is to prevent it from happening. The old adage of "stay off the field until its fit to work" still applies. However, the possible severe economic repercussions of delaying planting, harvesting, or other operations may outweigh compaction damage or loss. The dilemma farmers face in a wet spring or fall is not easy to resolve.

Since farmers need to be in the field in less than ideal soil moisture conditions, minimizing or controlling compaction is the next best management option. This includes reducing axle load, proper inflation and size of tires, and band applying nutrients to maximize availability.

Your soil is your most important resource when growing a healthy and profitable crop. Preventing soil compaction will increase water infiltration and storage capacity, timeliness of field operations, decrease the stress on plant roots, and decrease disease potential.

Acknowledgements:

The author wishes to thank Dr. Dave Franzen and Dr. Joe Pikel for their constructive comments when reviewing this publication.

References

1. Abu-Hamdeh, N.H., T.G. Carpenter, R.K. Wood, R.G. Holmes. 1995. Soil Compaction of 4 Wheel Drive and Tracked Tractors Under Various Draft Loads. SAE Technical Paper #952098.

2. Abu-Hamdeh, N.H., T.G. Carpenter, R.K. Wood, R.G. Holmes. 1995. Combine Tractive Devices: Effects on soil Compaction. SAE Technical Paper#952159.

3. Daum, D.R., R.F. Shipp. 2004. Agricultural Soil Compaction- Causes, Effects, and Cures. Penn State University publication B-79.

4. DeJong-Hughes, J.M., J.B. Swan, J.F. Moncrief, W.B. Voorhees. 2001. Soil Compaction: Causes, Effects and Control (Revision). University of Minnesota Extension Service BU-3115-E.

5. Krmenec, A.J. 2000. Vehicle traffic and soil compaction. Poster at Midwest Farm Progress Show, IL.

6. Reichenberger, Larry. 2002. Harnessing all your horsepower. Successful Farming, March 2002 edition, pp. 34-38.

7. Sidhu, D., S.W. Duiker. 2006. Soil compaction in conservation tillage: Crop impacts . Agronomy Journal. 98:1257-1264.

8. Soane, B.D., and C. van Ouwerkerk. 1994. Soil compaction in crop production. ISBN 0-444-88286-3. Chap. 12, pp 265-286.

9. Voorhees, W.B., W.W. Nelson, and G.W. Randall. 1986. Extent and persistence of subsoil compaction caused by heavy axle loads. Soil Sci. Soc. Am. J. 50:428-433.

10. Voorhees, W.B., C.G. Senst, and W.W. Nelson. 1978. Compaction and soil structure modification by wheel traffic in the Northern Corn Belt. Soil Sci. Soc. Am. J. 42:344-349.

11. Wolkowski, R., B. Lowery. 2008. Soil Compaction: causes, concerns, and cures. University of Wisconsin Extension publication #A3367.