The Soil Management Series

Compaction

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THE SOIL MANAGEMENT SERIES:

Publications to help you get more from your soil

Whether you grow a few acres of vegetables for local markets, or two thousand acres of corn and soybeans for international markets, you depend on top performance from your soil. The Soil Management series is aimed at improving soil performance. Because each farm is unique, the series will not tell you the "best way" to manage your soil. Only you can decide that. Instead, it will help you make more effective use of recommendations from the university, consultants, and other advisors.

Agronomic recommendations are typically made for broad climatic regions or soil types, but farmers are increasingly interested in fine-tuning and customizing management practices to fit their unique situation and variability across the land. One example of this trend is precision agriculture technology. The goals of a "fine-tuning" approach to land management are to use resources more efficiently, improve profits, and preserve the profitability and health of the land into the future. To fine-tune agronomic practices, farmers need to monitor the variation across the land from year to year, treat different parts of each field differently, and perhaps run personalized experiments to learn what works best on an individual farm.

This series will help by providing the background science needed to monitor soil and to understand how you can modify general recommendations to suit the needs of your farm. Each publication consists of the following sections that feature basic information, practical applications, and places to look for more help:

THE SOIL MANAGER —explains management options for improving your soil.

THE SOIL SCIENTIST —reviews the soil science principles that are important to production agriculture.

YOUR FARM —helps you apply what you are reading to your own farm.

WHAT'S NEXT? —wraps up the chapter by helping you assess your operation and soil.

FURTHER RESOURCES —lists people and publications to consult for more information.

Titles in the Soil Management Series include:

1) Soil Management (BU-7399)
2) Compaction (BU-7400)
3) Manure Management (BU-7401)
4) Organic Matter Management (BU-7402)
5) Soil Biology and Soil Management (BU-7403)

Copies of the individual titles and the complete series (PC-7398) can be ordered from the University of Minnesota Extension Service Distribution Center, 405 Coffey Hall, 1420 Eckles Avenue, St. Paul, MN 55108-6068. To order by e-mail: order@extension.umn.edu
or by credit card: (800) 876-8636.

Compaction

When is a field dry enough to plant or harvest? Every farmer faces the dilemma of balancing the need for timely planting and harvest against the long-term compaction damage caused by driving on wet soil. The consequences of this decision are becoming more and more serious as equipment becomes heavier and technology allows operation in wetter soil conditions.

Why is compaction such a concern?

Even if your soil has enough nutrients, plants will grow poorly if they cannot reach the nutrients or get enough air and water. Yields are lower and input costs may be higher on compacted soils because they:

- are harder for roots and seedlings to grow through. Poor root development means plants are more likely to be stressed by dry, wet, or low fertility conditions.
- drain more slowly in the spring or after heavy rains.
- hold less water.
- are a poorer environment for the soil organisms that cycle nutrients.

Are you doing all you can to avoid compaction risks?

Subsoil compaction is difficult or impossible to treat, so prevention is essential. This publication will discuss your options.

In this publication

The effects of surface compaction.

Notice the slow emergence of sugar beet seedlings in the tire tracks of the last tillage operation.

Photo courtesy of Caterpillar®.

SIX STEPS TO MINIMIZING COMPACTION

1) Stay off wet soil.
2) Keep axle loads low (below 5 tons).
3) Reduce ground contact pressure.
4) Use a controlled traffic system.
5) Reduce trips.
6) Increase soil organic matter levels.

These are significant factors to consider as you try to reduce compaction in your fields. Different kinds of compaction problems have somewhat different solutions. (See page 10 for descriptions of types of compaction.)

1) Stay off wet soil

Machines or cattle traveling on very wet soil will cause significant compaction, even if you have tracks, duals, or a light load (though light loads only create surface compaction). Letting soil dry for even one or two more days can greatly reduce soil damage. When you assess the moisture of your soil, check the soil at tillage depth as well as at the surface.

Staying off wet fields is rarely a simple decision. It requires weighing yield losses this year (caused by late planting or harvest) against losses for the next few years (caused by compaction). One way to reduce the frequency of this dilemma is to reduce the amount of field work that must be done during any window of time. Then you will have a better chance of being able to wait a couple more days for the soil to dry. Look at how your labor requirements are spread over the year on your farm. Compare this to the number of days that are typically available for doing field work. You might change your labor cycles by:

- diversifying crops so field operations are spread over time.
- using wider equipment so work can be finished more quickly. (With wide equipment, a smaller area of the field is driven over and compacted. Balance this with the disadvantage of using heavier equipment.)
- hiring extra help and equipment during key times.
- considering alternative tillage, planting, and fertilizer programs.

2) Keep axle loads low

Subsoil compaction is rare with axle loads under 5 tons and highly likely with loads greater than 10 tons per axle. (Some surface compaction is likely with any load.) Although increasing the footprint of the tractor (such as by adding duals) reduces surface compaction, it does not change the axle load and will have little effect on reducing subsoil compaction.

Implement	 100 HP tractor 14,000 lbs	 4WD tractor 30,000 lbs	 Empty 6-row combine 25,000 lbs	 Full 6,000 gal manure applicator 65,000 lbs	 Full 750-bu single axle grain cart 50,000 lbs
Axle weight	3.5 tons/axle (w/o load)	7.5 tons/axle (w/o load)	10 tons on front axle	10-15 tons/axle (2 or 3 axles)	22 tons/axle

3) Reduce ground contact pressure

Ground contact pressure is the pounds per square inch exerted on the soil by equipment. It is determined by the axle weight and the size of the "footprint" (the area of the tires or tracks in contact with the soil). Increasing the size of the footprint can reduce surface compaction.

One way to control contact pressure is to reduce tire pressure. As a rough rule, tires put one to two pounds more pressure on the soil than their air pressure. For example, a tire inflated to 25 psi will put 26 to 27 psi of pressure on the surface soil. A tire inflated to 15 psi will only put 16 or 17 psi of pressure on the soil. Low pressures increase the risk of rim slippage and tube leaks, so talk to your implement dealer or other advisor about the appropriate pressure for your equipment and field situations. Radial tires tolerate much lower inflation pressures than bias-ply tires and may be worth the investment to prevent compaction.

4) Use a controlled traffic system, and 5) reduce trips

Using tires in tandem (one directly behind the other) or consistently driving in the same lanes has two benefits. 1) Most compaction is caused by the first pass of a tire. Subsequent passes do not increase compaction as much as the first, and traction is better. 2) A much smaller portion of the field is compacted so roots have plenty of non-compacted soil to explore.

Designing a system of traffic lanes used during all field operations requires that all equipment have the same distance between wheels. Controlling traffic and minimizing trips across the field is especially important in no-till situations where surface compaction is not regularly loosened.

6) Increase organic matter levels

At the same water content and machinery weight, a soil with more organic matter will suffer less compaction. Organic matter (and the associated biological activity) protects soil from compaction by "cushioning" aggregates and increasing the stability of aggregates.

Want to know more?

See Further Resources for contact information

About building organic matter
Organic Matter Management and *Soil Biology* (BU-7402 and BU-7403 in this series).

About the relationship between organic matter and compaction
"The role of organic matter in soil compactability: a review of some practical aspects" by B.D. Soane (1990) *Soil and Tillage Research* 16:179-201.

QUESTIONS AND ANSWERS

How can I minimize compaction in the short term? (or: It's been raining for two weeks and the corn is ripe. Now what?)

Equipment adjustments can be more important than what kind of tracks or wheels you drive on. Talk to an implement dealer, Extension educator, or other advisor about the optimum wheel size, inflation pressure, load size, ballast size, and ballast position for your equipment and field conditions.

If you must go out on wet soil, the effects of surface compaction can be reduced with duals, flotation tires, and tracks. They provide traction and reduce ground contact pressure.

Work the driest soils first to give the wet areas more time to dry. This may mean dividing large fields into smaller parts, and following contours instead of straight lines.

What difference do soil amendments make?

It is unlikely that any soil amendment will directly loosen compaction. In fact, fertilizer and irrigation can increase compaction problems by reducing a plant's incentive to grow deep roots. Root growth may be an important tool for controlling compaction. Anything that assists plant growth–nutrients, lime, water–will help crops overcome compaction in the short run, but if it does not enhance the extent of root growth, it may make the problem worse in the long run.

Organic amendments help prevent and loosen surface compaction by promoting biological activity and by raising the soil organic matter levels. Soils with higher levels of organic matter resist compaction more effectively.

Want to know more?

About proper equipment adjustment
Begin with your equipment owner manuals, implement dealer, and Extension educator. Also see: *How to Get the Most from Radial Ply Tractor Tires: A Guide to Select the Correct Inflation Pressure,* 1994.

Should I buy tracks or wheels?

The decision whether to use a tractor with tracks or wheels is not simple. Either can cause significant compaction if misused or improperly adjusted. Any system will cause more compaction and be less time and energy efficient if it is not properly adjusted and ballasted for the load and soil conditions.

Tracks and flotation tires may make it possible to drive on wetter soils, allowing a farmer to create more severe compaction.

An advantage of tracks is their large footprint and low ground contact pressure. This footprint is spread front-to-back instead of side-to-side (as are duals or triples), so less of the field is compacted. The disadvantages are that the weight of the tractor is on a given volume of soil for a longer period of time, and the vibration of the track increases compaction.

Studies suggest that tracks reduce surface compaction compared to using wheels. However, it is not clear whether they reduce deep compaction. They may seem to have lower axle weights because the total weight of the tractor is spread over more than two axles, but the axles are close together and may not act like separate axles when applying pressure to the soil.

Does compaction increase under reduced tillage systems?

The reduction or elimination of tillage does not necessarily mean that surface compaction will become a serious problem, but compaction is managed differently in low-till systems and deserves monitoring.

The increasing levels of near-surface soil organic matter help soil resist compaction. Increased surface residue encourages the activity of organisms that burrow through the soil and enhance soil aggregation, but it may take a few years for biological activity to increase substantially. Because there is no regular tillage to loosen soil, traffic lanes become more important for preventing surface compaction.

HOW TO TREAT COMPACTED SOILS

Wait

If you stop compacting the soil, yields will probably return gradually to pre-compaction levels. The process of rehabilitating compact soils is not well understood. Researchers have seen yield recovery even when physical measurements (such as bulk density) have not returned to pre-compaction levels. Medium to heavy soils are more susceptible to severe compaction and take longer to recover.

You cannot rely on frost action to relieve compaction each year. It may have some effect on surface compaction, but does little to ease deep compaction. Subsoil usually goes through only one freeze/thaw cycle each winter.

USDA researchers compacted soil at the Waseca Experiment Station in 1981 by using ten-and twenty-ton axle load equipment. For the first 2 to 3 years, corn yields on the compacted plots were less than those on the non-compacted plots. During

the next decade, the one-time compaction event caused reduced yields during years of very high or low rainfall, but not under optimal moisture conditions. (See references to this research on page 11.)

Loosen the soil

Normal **tillage** relieves surface compaction.

Roots are invaluable for loosening soil. Deep tap-rooted plants will grow through hardpans (such as tillage pans) and deep compaction. When they die, the root channels become conduits for water and other roots. There has been minimal research linking yield improvements with crops used to loosen compaction, so there is little guidance about which plants to use and how to grow and manage them. The strong tap roots of alfalfa and sweet clover are thought to be useful in treating subsoil compaction. These plants may need three or more years to be effective. Other useful antidotes to deep compaction may include red clover, lupines, soybeans, reed canarygrass, burdock and dandelion. Any grass (especially quackgrass) loosens surface compaction.

Earthworms and other soil invertebrates loosen soil and create channels for root growth and water movement. Attract earthworms by regularly adding organic matter.

Subsoiling (or deep tillage) is sometimes helpful, but has not been found to be a reliable cure for deep compaction in the upper-Midwest. If you think it might help on your farm, consider these guidelines.

- Be sure compaction is the problem. Explore your fields with a shovel or probe to learn where it is compacted and how deeply.
- It may be most cost effective to deep-till only the worst areas, such as headlands.
- Be sure soil is dry so it fractures. Cutting through moist soil will have little effect.
- Plan to avoid future compaction. One pass with a heavy implement will wipe out your investment in deep tillage.

Denitrification is the conversion of nitrate to nitrogen gasses that are lost from the soil. The conversion is done by soil bacteria that live in low oxygen (e.g., saturated) conditions, which are more common in compacted soils.

Compensate for decreased nutrients and water

If you know what is causing a yield loss, it may be possible to partially compensate by increasing fertilizer or irrigation inputs. For example, it may be necessary to use split applications of nitrogen to minimize denitrification losses, or to use row applications of phosphorus and potassium to improve availability. Keep in mind that these short-term fixes may aggrevate compaction problems. They increase traffic and may reduce the extensiveness of root growth.

WHAT IS COMPACTION?

Compaction is a change in soil structure, not just an increase in soil density. Healthy soils have a diversity of pore sizes, while compacted soils have mostly small pores.

During the compaction process soil aggregates are pushed closer together. This reduces the size of pores, the continuity of pores, and the size and stability of aggregates. Only under severe compaction will aggregates break down.

Because the change in soil structure is complex, there is not a simple relationship between increased soil density and decreased crop yield. The changes in soil structure affect the movement of water, air, roots, and soil organisms through the soil, so the effect on yield depends on the weather, the amount and depth of compaction, and the crop type.

Want to know more?

About aggregates and pores

Aggregates are tiny clumps of soil particles. Pores are the network of spaces between aggregates. See *Soil Management* (BU-7399 in this series) for more information.

What causes compaction?

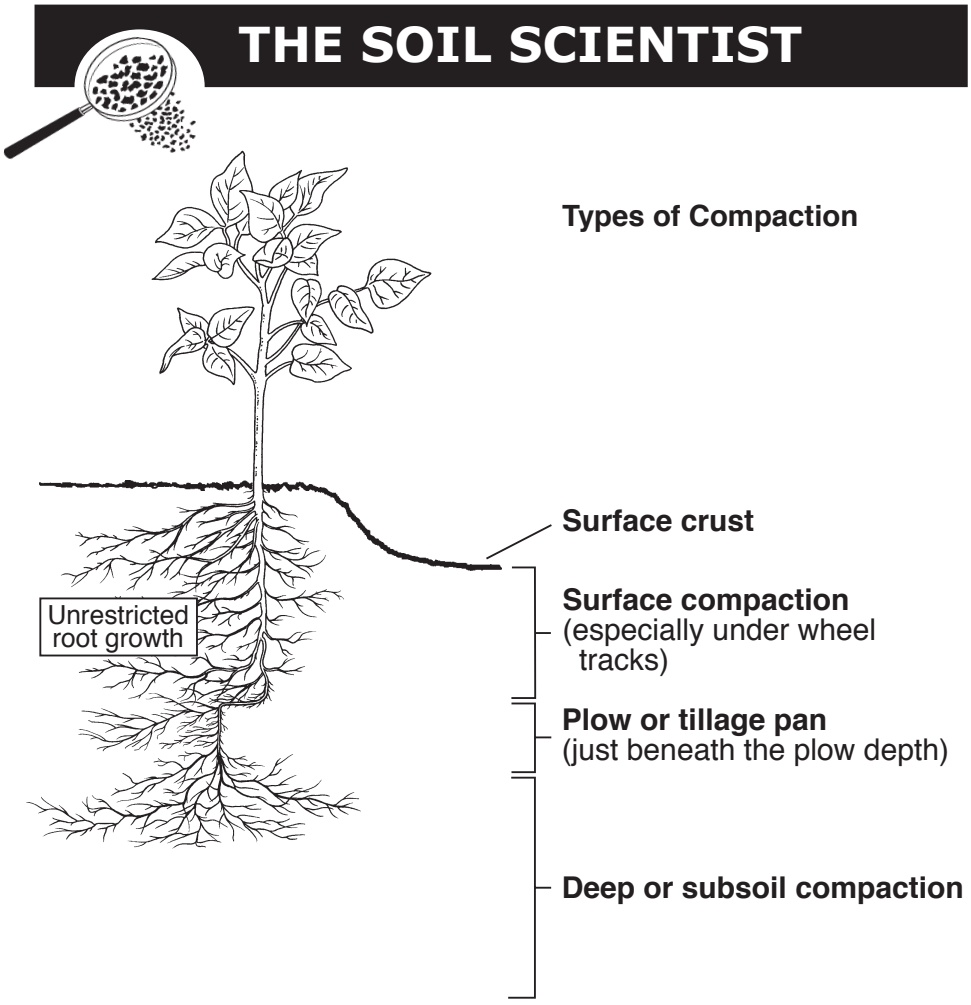
Wheel traffic is the main cause of compaction on most farms, though rain, drying, and animal traffic also contribute on certain soils. The amount of compaction depends on the size and weight of the equipment, the moisture level of the soil, and the type of soil (soils high in clay or low in organic matter compact more readily).

How does compaction occur?

A typical chain of events begins in the fall when heavy harvest equipment pushes soil aggregates closer together and reduces soil drainage. The next spring, the soil will not drain as quickly, and the short window of opportunity for spring field work becomes even shorter. Farmers are forced to work wet soils and more compaction occurs.

Spring tillage will loosen surface soil, but seeds in the tire tracks may have trouble emerging from the packed soil, and roots will not spread as easily. To compensate for the poor root growth, a farmer may increase the amount of fertilizer or use split applications. The extra fertilizer may mean more traffic, and may discourage extensive root growth deep into subsoil where they can help alleviate compaction.

The process of loosening soil might begin when soil swells from a good rainfall, and then shrinks during a dry spell. The swelling and shrinking causes cracks that can be filled by roots or soil organisms that further improve soil structure. Freezing and thawing also creates cracks, especially near the surface where soil may freeze and thaw several times in a season. But all of this is a slower process than the compaction caused by a 20-ton combine or grain cart.



Types of compaction

Not all cases of soil compaction are the same. Each type has different causes and treatments.

Surface crusting reduces seed emergence and water infiltration. It is caused by the impact of rain drops on weak soil aggregates. Soils with high organic matter, high biological activity, or high sand content are less likely to form crusts.

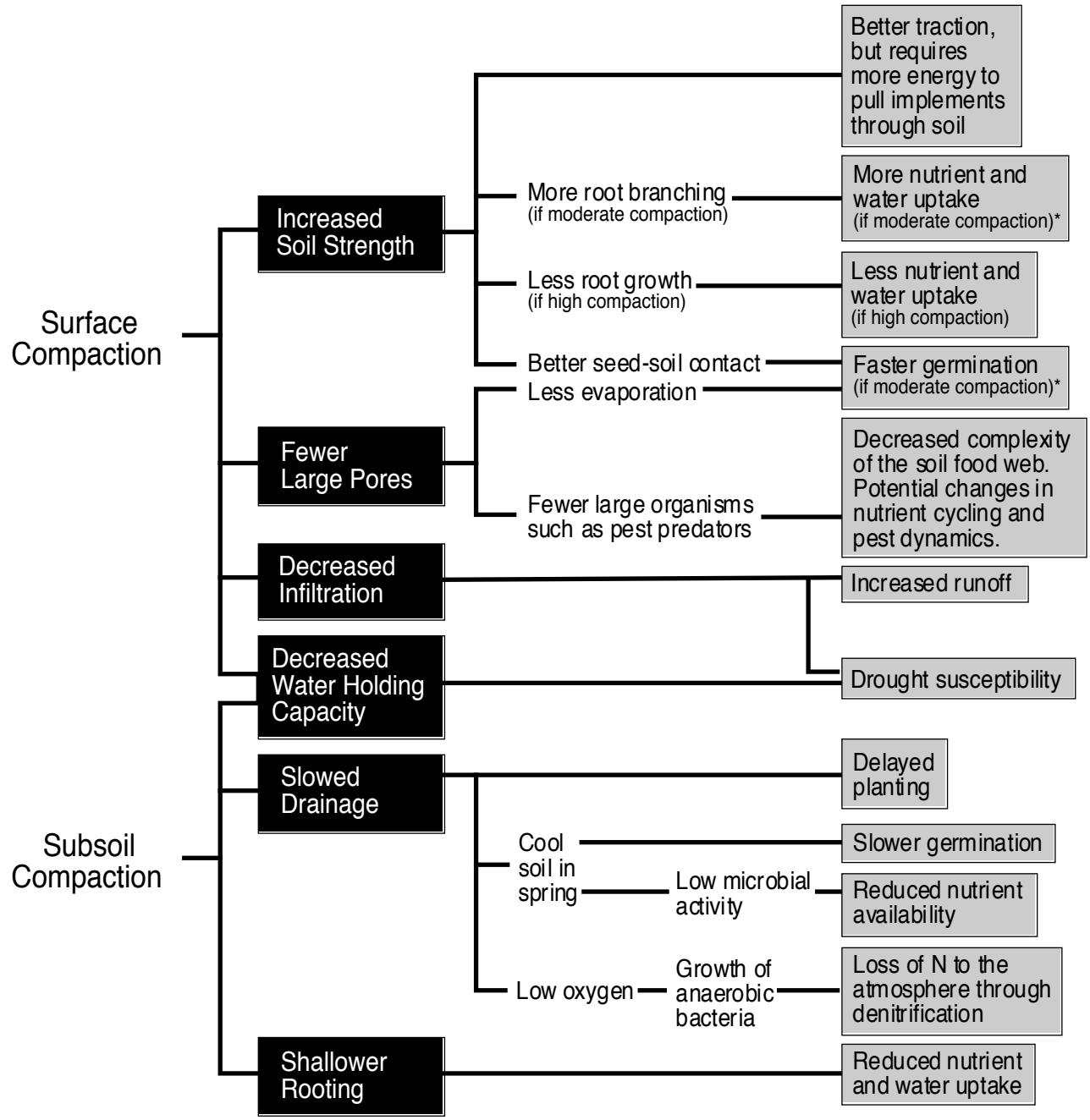
Surface compaction occurs from the surface down to the tillage depth. It can be loosened by normal tillage, root growth, and biological activity. The degree of surface compaction is determined by the moisture in the soil at the time of compaction and the ground contact pressure (measured in pounds per square inch or psi) of equipment or animals.

Subsoil or deep compaction lies beneath the level of tillage. Ground contact pressure and the total weight on the tire (the axle load) significantly affect the amount of subsoil compaction. Deep compaction is difficult to eliminate and may permanently change the soil structure. Prevention is important.

Plow pan or tillage pan is subsoil compaction that is only a few inches thick and lies directly beneath the normal tillage depth. It develops when the depth of tillage is the same from year to year, or when the rear wheel of the tractor rides in the moldboard plow furrow.

HOW DOES COMPACTION AFFECT PRODUCTIVITY?

Compaction changes several structural characteristics and functions of soil. This makes it difficult to predict the effect of compaction on crop yield or on the need for inputs such as fertilizer and irrigation. The diagram below summarizes how compaction affects plant growth and input use.



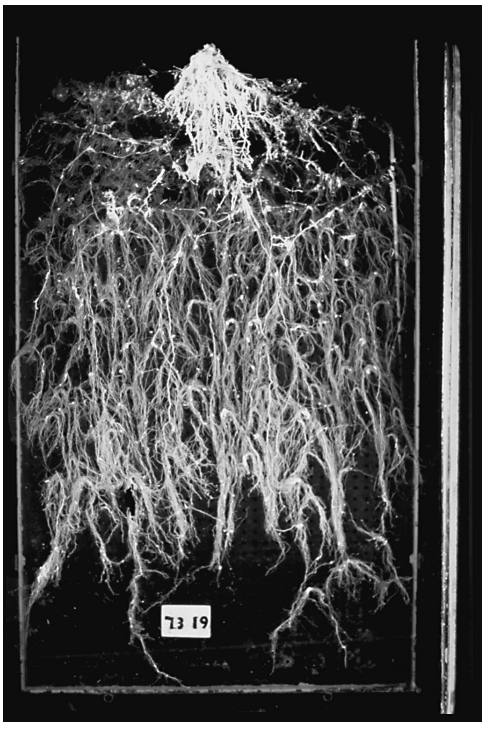
*Moderate compaction is that created by less than 5 ton axle loads on dry soil.

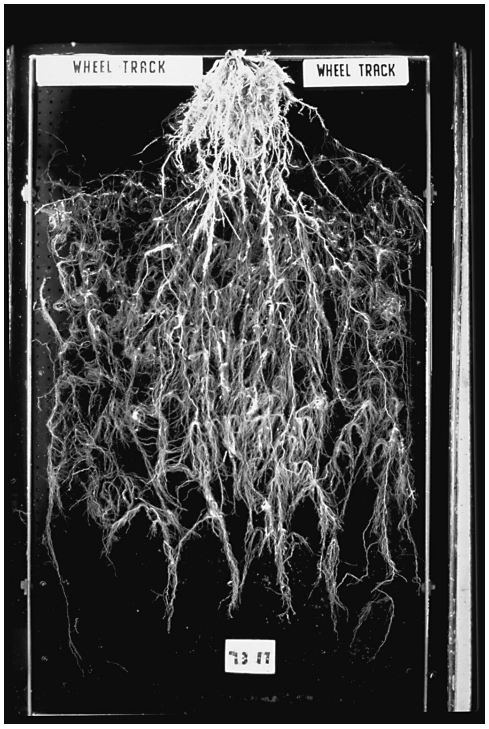
Is compaction always bad? Subsoil compaction is probably never beneficial, but some people see benefits from moderate surface compaction (i.e. compaction created by less than five-ton axle loads on dry soil). For example, if recently-tilled soil is excessively loose, some compaction directly around the seed promotes germination. In drier climates (less than 14 inches of rain in the growing season), moderate surface compaction may improve yields by promoting root branching and phosphorus uptake, and by increasing the water holding capacity of the soil.

How much does compaction reduce yield?

The effect of compaction depends on

- the amount and depth of compaction,
- the type of soil (high sand and organic matter levels reduce the effects of compaction),
- weather (under good conditions, yields may not suffer at all), and
- the crop. (For example, corn is sensitive to deep compaction but is less affected by surface compaction. The opposite is true for soybeans.)





These are the roots of corn plants grown at the University of Minnesota Lamberton Research and Outreach Center (ROC). The plant on the left had no wheel traffic compaction between the rows. The plant on the right had wheel tracks on both sides. Wheel tracks were made by three wheel passes (planting, spraying, and cultivation) with axle loads of less than five tons. Note the lack of root growth under the wheel tracks. Plants like this cannot access much of the P and K broadcast over a field.

Photos courtesy of Ward Voorhees

THE SOIL SCIENTIST

Researchers have reported yield losses due to compaction of greater than 40%, but they have also seen yield increases from mild surface compaction during dry years. At the Waseca Research and Outreach Center in southern Minnesota, subsoil compaction caused yield losses of more than 25%. Researchers created the compaction in 1981 by driving over the Webster clay loam (38% clay) with 10- and 20-ton axle loads. Corn yields in the first year after compaction were:

170 bu/ac	on non-compacted soil
155 bu/ac	on soil compacted with a 10-ton axle load
125 bu/ac	on soil compacted with a 20-ton axle load

The cost of compaction

In addition to reduced yields, crops grown on compacted soils may have higher input costs and are more sensitive to inadequate nutrient and moisture levels. Researchers are just beginning to develop tools that will predict the financial cost.

Want to know more?

About how compaction affects yield of various crops

Soil Compaction—Causes, Effects and Controls. 1987. University of Minnesota Extension Service BU-3115.

"Responses of temperate crops in North America to soil compaction" by W.B. Voorhees. (1994) p. 265-286 in *Soil Compaction in Crop Production*, edited by B.D. Soane and C. van Ouwerkerk.

"Relationship between wheel-traffic-induced soil compaction, nutrient availability, and crop growth: A review." R.P. Wolkowski. (1990). *Journal of Production Agriculture* 3:460-469.

WHAT'S NEXT?

Do you have a compaction problem on your farm? Is it affecting your bottom line now, or will it in the future? You can begin to answer these questions by assessing your risk for compaction and monitoring your farm for compaction.

ASSESSING COMPACTION RISK

Use "Six Steps to Minimizing Compaction" on page 2 to analyze your operation. Here are some questions you might ask.

- ✔ **Do you have enough time for field work in the spring?** How many days does your field work require? Compare this to the number of days suitable for field work in the spring. (Your nearest University Research and Outreach Center may have historical data on the number of days suitable for field work.) You might learn that for 1 in 10 years the weather will not allow you enough days to finish field work by the latest profitable planting date. Maybe the ratio is 3 in 10 years, or 1 in 20 years. Are you comfortable with that ratio? If not, how might you change your operation so you feel less pressure to drive on wet fields?
- ✔ **What is the axle weight of each of your pieces of equipment?** Those over 10 tons pose a significant risk for subsoil compaction.
- ✔ **When is the last time you evaluated your tractor tire pressure or the amount and location of ballast?** Ask your Extension educator or equipment dealer for the latest advice on these.
- ✔ **What would it take to establish a controlled traffic system or to increase soil organic matter levels?**

Your Farm

After you assess your risk of compaction you may have some ideas for changes you could make. At the end of Soil Management (BU-7399, Your Farm #7) you made a list of management practices to consider changing. Go back to that plan and list some concrete management goals for reducing compaction.

If you have not completed Soil Management, use this opportunity to begin jotting down possible management changes.

WHAT'S NEXT?

FOUR WAYS TO MONITOR COMPACTION

1. Use a soil probe

A penetrometer is a tool that measures soil strength when pushed into the soil. High readings can mean that soil is compacted or that it is dry, so consider the soil moisture level when interpreting readings.

With a bit of practice you can locate compaction problems without special equipment. Push a metal rod, stiff wire, or a fiber-glass fence pole into the ground using even pressure. Compare the feel of different parts of a field such as headlands, between rows, or in low spots. (Remember that wet soils are easier to push through.) Feel for changes in density as you push through the soil and note the depth of the compacted layer.

2. Watch for indicator weeds

Healthy stands of bindweed, quackgrass, mustards, velvetleaf (button weed), horse nettle, and pineapple weed are thought to indicate hardpans.

Compacted soil that is poorly drained and going acid will support sorrels, dock, horsetail, and lady's thumb. Foxtail also likes compacted, poorly drained soils.

3. Study roots

Whenever you dig a hole, for any reason, look at the roots. Roots turn sharply when they run into a compacted area and are less common within dense layers.

Some people pull up a plant (a weed will do) and study the fine root hairs. Normally, they grow straight out, perpendicular to the root. If they grow out in other directions, it may indicate compaction.

4. Measure soil bulk density

Soil density is the weight of the soil divided by its volume. It is an indicator of compaction, but not always a good indicator of how plants will respond to the compaction. Soil texture is one explanation for this. High density in a sandy soil might not restrict root growth, while root growth in clay soils could be restricted at the same density.

Instructions for measuring bulk density are in the USDA Soil Quality Test Kit. Ask for it at your local Soil and Water Conservation District office, or on-line at: http://www.statlab.iastate.edu/survey/SQI/kit.shtml

FURTHER RESOURCES

Compaction Specialists

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Publications

Academic articles are available in major research libraries, such as at the University of Minnesota.

"Corn growth and yield as affected by surface and subsoil compaction" (1989) W. B. Voorhees et al., *Agronomy Journal* 81:294-303.

"Extent and persistence of subsoil compaction caused by heavy axle loads." (1986) W. B. Voorhees et al., *Soil Science Society of America Journal* 42:344-349.

How to Get the Most from Radial Ply Tractor Tires: A Guide to Select the Correct Inflation Pressure. 1994. This free publication comes from the Energy in Agriculture Program—a program of the California Energy Commission. It is available at www.energy.ca.gov/agprogram/index.html or by writing: Biological and Agricultural Engineering Department, 2030 Bainer Hall, University of California-Davis, Davis, CA 95616. Phone: 916-752-0102.

"Relationship between wheel-traffic-induced soil compaction, nutrient availability, and crop growth: A review." (1990) R. P. Wolkowski, *Journal of Production Agriculture* 3:460-469.

"Responses of temperate crops in North America to soil compaction" (1994) W. B. Voorhees, p. 265-286 in *Soil Compaction in Crop Production*, edited by B. D. Soane and C. van Ouwerkerk.

"The role of organic matter in soil compactability: A review of some practical aspects" (1990) B. D. Soane, *Soil and Tillage Research* 16:179-201.

Soil Compaction—Causes, Effects and Controls. 1987. J. B. Swan, J. F. Moncrief, and W. B. Voorhees. University of Minnesota Extension Service BU-3115. 12 pgs.
Don't be deterred by the old publication date—this has lots of good information. It includes examples of research results, and specifics about effects of compaction on individual crops.
Order by calling 1-800-876-8636.

Soil Compaction Issues Related to Soybean Production. 1996. Ward B. Voorhees. From the Midwest Soybean Conference, August 1996, in Des Moines, Iowa.
Ask Ward Voorhees for a copy. See contact information above.

Notes

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The Sustainable Agriculture Information Exchange

This publication is part of a series developed through the Sustainable Agriculture Information Exchange, a clearinghouse of sustainable agriculture information and materials in Minnesota. These informational materials are accessible to the public by phone (toll-free), fax, e-mail, or World Wide Web.

The Information Exchange works to bridge the gap between the need for timely, practical information about sustainable agriculture and existing resources and information; to identify gaps in research and education and direct funding and support to address them; and to promote education and discussion of issues relevant to the sustainability of agriculture.

To ensure that all of the Information Exchange's publications are applicable and user friendly, they are developed by teams and reviewed by individuals who will use the material, including farmers, researchers, Extension educators, other agricultural professionals, and members of the agricultural community. Information Exchange activities are guided by an advisory committee that includes farmers, researchers, and other agricultural community interests and are carried out in cooperation with the Minnesota Department of Agriculture-Energy and Sustainable Agriculture Program and the University of Minnesota Extension Service.

The Information Exchange is part of the Minnesota Institute for Sustainable Agriculture (MISA), a partnership between the University of Minnesota–College of Agricultural, Food, and Environmental Sciences and the Sustainers' Coalition, a group of individuals and community-based non-profit organizations.

Other publications in this series include:

- **Discovering Profits in Unlikely Places: Agroforestry Opportunities for Added Income** (University of Minnesota Extension Service Distribution Center BU-7407)
- **Organic Certification of Crop Production in Minnesota** (University of Minnesota Extension Service Distribution Center BU-7202)
- **Whole Farm Planning: Combining Family, Profit, and Environment** (University of Minnesota Extension Service Distribution Center BU-6985)

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