Soil Compaction in Annual Crop Production:

Causes, Impacts, and Solutions

Introduction

Soil compaction is commonly understood to be a serious and widespread concern for agricultural production and environmental health (Hamza and Anderson 2005). It results in poor soil structure, restricted water movement, and reduced biological activity, ultimately reducing crop yield and other critical soil functions (Cresswell and Kirkegaard 1995; Bushamuka and Zobel 1998). Additionally, it can cause environmental damage by increasing the potential for soil erosion and associated surface water pollution (Dexter 1988; Soane and Ouwerkerk 1995). This damage and its consequences are particularly concerning given that soil regenerates so slowly that it can effectively be considered a nonrenewable resource. This publication examines how agricultural activities cause compaction, under what conditions soils are particularly susceptible to compaction, how it is identified and measured, and how it can be repaired using implements and through management practices, such as cover cropping.

Anthropogenic Causes of Compaction

Soil compaction is “the densification and distortion of soil by which total and air-filled porosity are reduced, causing deterioration or loss of one or more soil functions” (van den Akker 2008). While hardened or chemically cemented soil horizons may arise naturally through soil-forming processes, most soil compaction is caused by human activity (Bengough and Mullins 1990; Spoor 2006).

Field operations that include primary and secondary tillage, fertilizer and pesticide application, transplanting, and sowing are commonly done with heavy equipment (Figure 1). Each pass over the field increases the severity of compaction (Shah et al. 2017). Severity of the damage done by this vehicular traffic is due to essential factors, including axle load and the surface area of the machinery in contact with the soil (Alakukku et al. 2003). The total wheel load divided by the tire (or track) surface area that is in contact with the soil equals the ground contact pressure, which is the force that produces compaction in the soil below (Hamza and Anderson 2005; Nawaz et al. 2013). Compaction in the plowed topsoil layer is generally derived from ground contact pressure; on the other hand, subsoil compaction comes from both ground contact pressure and total axle load, which is the total weight of the vehicle divided by the number of axles (Håkansson and Reeder 1994; Alakukku et al. 2003).

Figure 1. Heavy equipment can cause both surface and deep soil compaction. (Figure credit: Gabriel LaHue.)

Theoretically, compaction from increasingly heavy tractors and implements can be lessened with greater tire surface area, but this has been difficult to achieve (Schjønning et al. 2015). For example, a study involving commonly used harvesters from 1958 to 2009 showed that ground pressures jumped by over 40% due to dramatic weight increases in the machinery despite an increase in tire size over that time frame. This has increased vertical stress

WASHINGTON STATE UNIVERSITY
EXTENSION

reaching the subsoil in recent years (Figure 2; Schjønning et al. 2015). Distributing the load of the equipment over more tire surface area can be accomplished in a few ways, some of which are easier to implement than others. Lower tire pressures and larger tires are effective, though larger tires are more expensive. Furthermore, when tires are at lower pressure, their increased width compacts more field area, albeit with less severity (Hamza and Anderson 2005). Other approaches include using equipment that has more tires or replacing tires with tracks (Alakukku et al. 2003; Schjønning et al. 2015).

Plowing and tillage also cause soil compaction, independent of the simple ground pressure exerted by tractor tires during these operations. Tillage can damage soil structure and decrease soil organic matter, especially when done frequently (Pagliai et al. 2004; Shah et al. 2017). Moldboard plowing exerts a shearing force that compacts the subsoil layer just below the cultivated layer (Figure 3), while wheel slip in the furrow can also cause additional compaction (Alakukku et al. 2003). Other tillage implements, such as disks, spaders, chisel plows, and cultivators do not apply the same pressure directly to the soil as moldboard plows, so they cause less compaction. They also shatter and loosen the soil more if used at an appropriate soil moisture level (Brady and Weil 2002; Pagliai et al. 2004).

Soil Susceptibility

A soil’s susceptibility to compaction is the product of complex interactions between many factors, though soil moisture is the most impactful (Figure 4). When the soil is dry, its strength and internal friction is greater. Pressure applied to dry soil may not meaningfully increase compaction (Kooistra and Tovey 1994; Batey 2009). Soil is most compactible when it is moist but below saturation, a fact utilized by road and building engineers striving for maximum compaction to support heavy loads. A typical soil is generally most compactible when the water content allows the soil to be hand-molded into a lump that sticks together after hand pressure is released but will then break cleanly into two sections when “bent.” If soil is drier than is optimum for this type of compaction, it will tend to crumble instead of break (CCIL 2021). While the knowledge that drier soils are less compactible could seemingly make compaction easy to prevent, the reality is far more complex. In many, if not most, modern production systems, the timing of field operations is based on production schedules or narrow weather windows rather than on soil moisture or soil health considerations (Wolfe et al. 1995). Consequently, producers are often incentivized to take their heavy equipment onto their fields when the soil is most vulnerable to compaction.

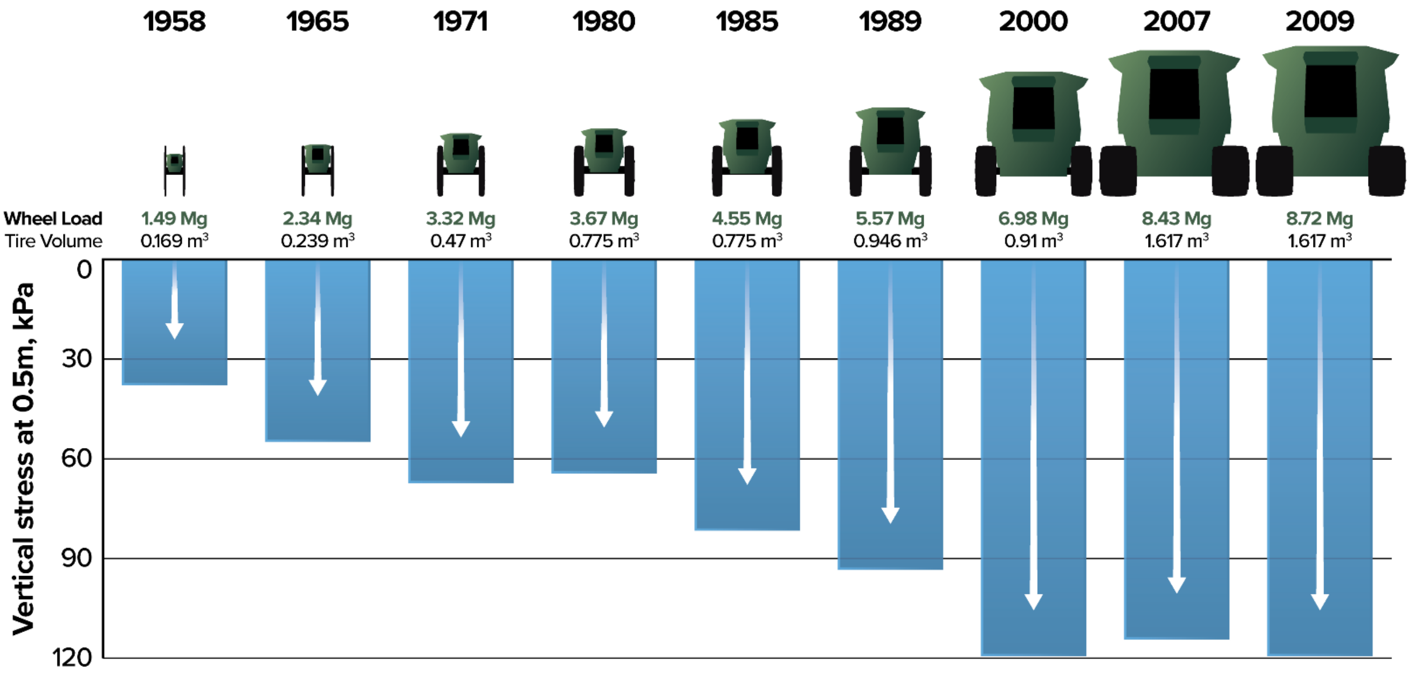

Figure 2 Wheel load, tire volume, and vertical stress for self-propelled combine harvesters produced from the Dronningborg factory (Randers, Denmark) from 1958 to 2009. Larger tire volumes have not reduced vertical stress as the size of machinery has increased. Adapted from *Driver-Pressure-State-Impact-Response (DPSIR) Analysis and Risk Assessment for Soil Compaction—A European Perspective* (Schjønning et al. 2015). Image credit: Andrew Mack.

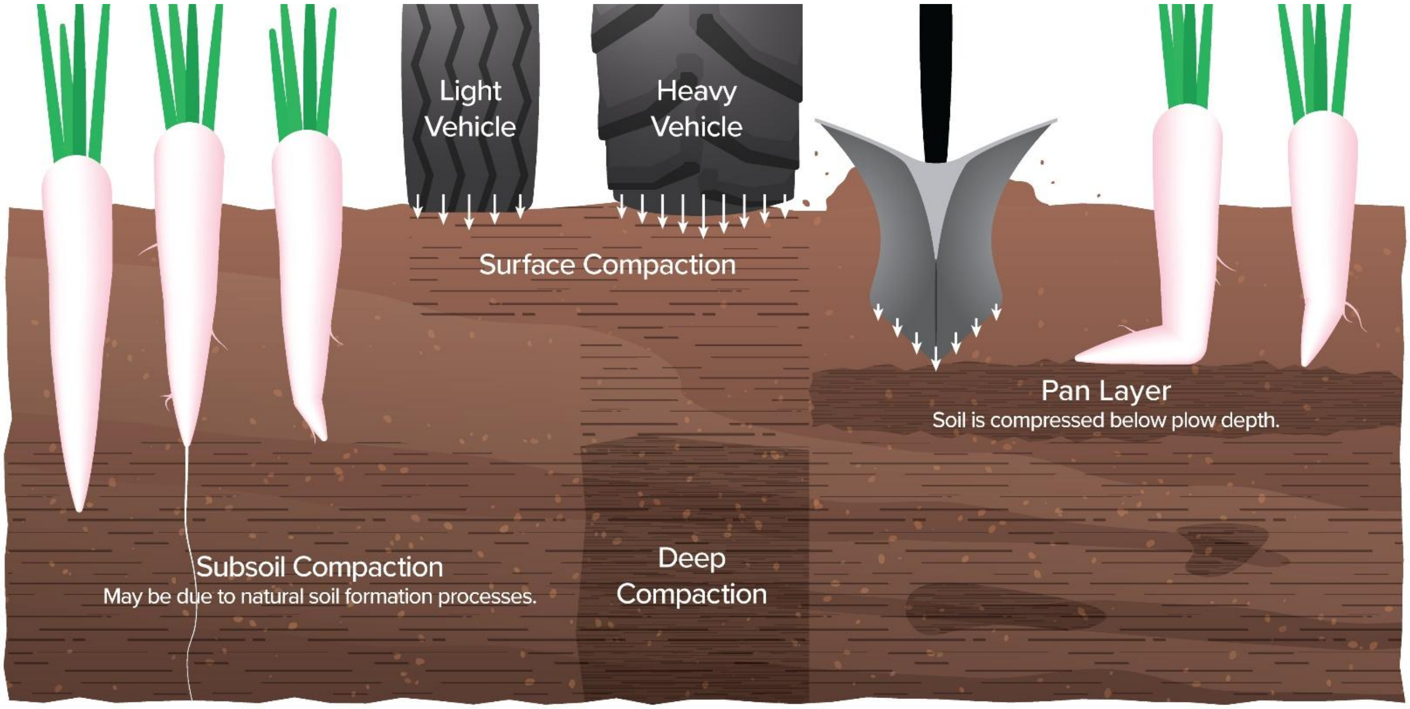

Figure 3. Natural and human-caused soil compaction. Vehicular traffic can cause both surface and deep compaction, while using implements such as moldboard plows can result in a pan layer. (Figure credit: Andrew Mack.)

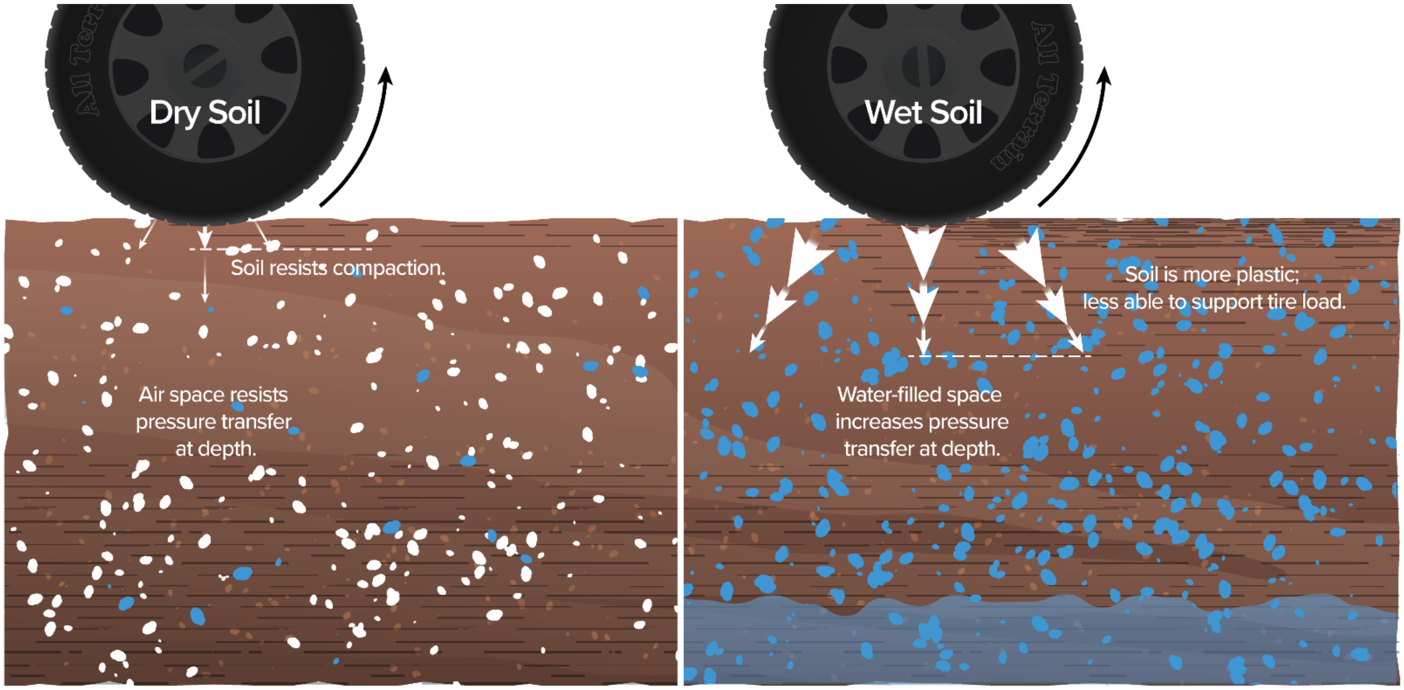

Figure 4. The impact of soil moisture on compaction. All soil types and conditions are susceptible to compaction, but the degree will vary with conditions. (Figure credit: Andrew Mack.)

Soil texture can also play a role in its susceptibility to compaction, though there is not a clear consensus on which soil textures are most susceptible to compaction, and all soils are susceptible to compaction to some degree. Nevertheless, multiple studies have reported that susceptibility to compaction can be greater for soils with a high silt content (Horn et al. 1995; Díaz-Zorita and Grosso 2000). In addition to soil texture, soil organic matter content can impact soil susceptibility to compaction. Organic matter assists in soil aggregation, making soils more resistant to compaction or increasing rebound following field traffic (Quirk and Panabokke 1962; Soane 1990).

Identification of Compaction

Since soil compaction can (and regularly does) go unnoticed, it is essential to have means of recognizing it and assessing its severity. The increase in density and reduction in porosity mentioned above is accompanied by an increase in soil strength, a reduction in saturated hydraulic conductivity (the ability of soil to move water through it), the diminished ability to diffuse gases, and, often, reduced crop yield. Bulk density is a direct measure of compaction (Figure 5, top left). Measurements of soil physical parameters, such as bulk density, are frequently variable across space and time (van den Akker 2008), so different types of measurements can complement each other.

Soil strength increases when a soil is compacted, potentially reducing the root elongation rate in the soil. Cone penetrometers, though they are larger and less flexible than roots and thus interact with the soil differently, provide the best method of directly measuring soil strength and resistance to root growth (Figure 5, bottom left) (Bengough and Mullins 1990). Studies have demonstrated that although penetrometers are theorized to approximate the resistance roots encounter, they encounter between two and eight times more resistance than roots (Bengough and Mullins 1990). They also do not adequately register small pores and channels, such as those made by roots and earthworms, which subsequent roots may use (Soane et al. 1987). Since soil strength varies with soil moisture, penetrometer measurements taken while the soil is at field capacity are the most accurate. Despite these issues, cone penetrometers are still an integral tool in gauging the resistance that roots experience in compacted soil (Bengough and Mullins 1990).

Reduced porosity results in a diminished ability of water to move through the soil profile, making saturated hydraulic conductivity another useful parameter to assess the impact of compaction on the soil (Figure 5, right photo). Since it is closely associated with the pore size distribution, this measurement can provide insight into gas diffusion capability and soil structure (van den Akker 2008). Saturated hydraulic conductivity varies greatly over space and time, but given the direct connection to an important soil function, it is still a useful measurement to assess soil compaction.

These parameters—bulk density, soil strength, and saturated hydraulic conductivity—can be used to assess compaction; however, none of these metrics individually excels at approximating a plant’s response to the conditions inherent in a compacted soil, much less when comparing different soil types. Consequently, researchers have proposed relative bulk density parameters to compare different soils (Håkansson and Lipiec 2000). Perhaps the most commonly used of these is referred to as the “degree of compactness,” which compares a soil sample’s bulk density to a reference sample of that same soil that has been subjected to a compression stress of 200 kPa (Håkansson and Lipiec 2000).

Impacts of Compaction on Soil Functions

Though soil compaction can be hard to detect, it can cause significant negative effects (Figure 6). Compaction reduces porosity and increases soil strength, disrupting the soil’s ability to transmit water and diffuse gases, which reduces soil biological activity and related biogeochemical processes. With infiltration and hydraulic conductivity degraded, compacted fields in flat areas may experience ponding. Ponding hinders the use of machinery and slows soils from drying in the spring, increasing the possibility of further compaction if field traffic begins while the soil is still too wet. In addition to ponding caused by surface compaction, water can become perched on top of the compacted subsoil layer (Horn et al. 1995).

Figure 5. Methods for monitoring soil compaction include bulk density (top left photo), penetration resistance (right photo), and saturated hydraulic conductivity (bottom left photo). (Figure credit: Douglas Collins.)

In sloped areas, the consequences can be more severe. Water will be more likely to run off the soil surface, carrying soil and nutrients from the topsoil. It may also carve rills into the soil (Figure 7). Topsoil losses from erosion of this type have been calculated to exceed 20 Mg ha^{-1} year^{-1} (Horn et al. 1995).

Healthy soil offers the benefit of filtering water as it works its way through the profile. In an uncompacted soil, though rapid preferential flow is possible, nutrients and pesticides are more likely to infiltrate into the soil, allowing opportunities for filtration, adsorption, or for microbes to break them down (Jorgensen et al. 1998; Vogel et al. 2000). However, with low infiltration rates and reduced saturated hydraulic conductivity due to soil compaction, runoff will increase, and eroded soil, nutrients, fertilizers, and pesticides can accumulate in surface water bodies (Soane and Ouwerkerk 1995).

Reduced pore space (particularly macropore space, as these are air-filled at field capacity) and greater susceptibility to ponding also means less space for air and a limited ability to diffuse gases (Shah et al. 2017). The consequent anaerobic conditions affect soil biology and chemical processes in ways that can cause negative environmental impacts. For example, denitrification, which is bacterially mediated, occurs only under anaerobic conditions (Ball et al. 2008). Increased denitrification results in increased emissions of nitrous oxide (N_2O), a potent greenhouse gas. For example, Ball et al. (2008) found that compacted soils had more water-filled pore spaces and an associated spike in N_2O emissions.

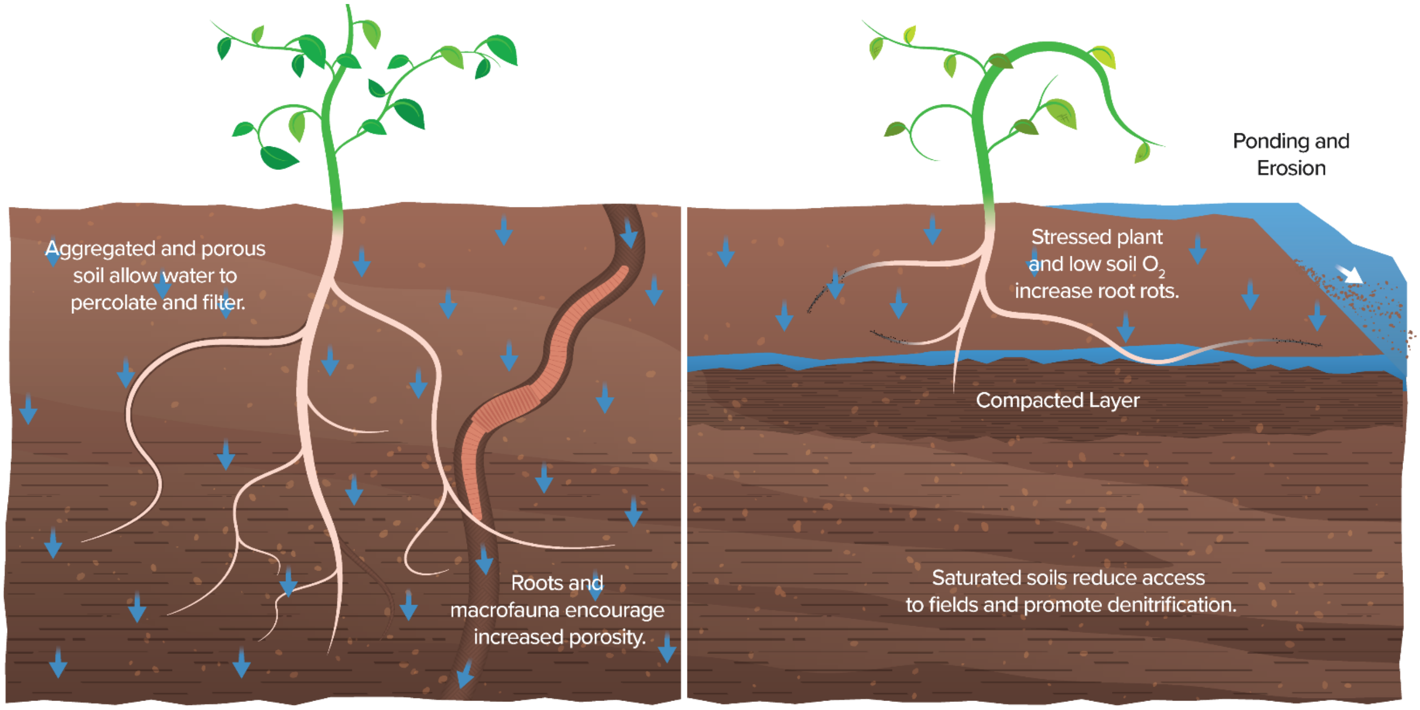

Figure 6. Compaction slows water infiltration, encourages ponding and erosion, and can lead to denitrification and stressed plants. (Figure credit: Andrew Mack.)

Denitrification also consumes nitrate that crops could otherwise use (Schjønning et al. 2015).

Besides increasing the activity of anaerobic denitrifying bacteria, compaction can harm soil quality as a habitat for soil macrofauna by limiting pore size diversity. The mobility of larger soil fauna, which play a crucial role in organic matter decomposition and nutrient cycling, may be restricted in compacted soils (Nawaz et al. 2013). Compaction can also reduce microbial populations (Pupin et al. 2009), yet at the same time, many plant-pathogenic organisms flourish in low-oxygen soils. Compaction has been found to worsen the impacts of root rot, a disease caused by soilborne pathogens, in some pea varieties (Fritz et al. 1995). Compaction has also been associated with the soilborne potato pathogens *Rhizoctonia solani* and *Spongospora subterranean* (Sinton et al. 2022). Since roots need an adequate supply of oxygen for respiration, the loss of air-containing pore space results in another stressor for the plant. The consequence of anoxic conditions is the utilization of fermentation in root cells rather than respiration, which is inefficient and, therefore, stunts plant development (Fukao and Bailey-Serres 2004).

A compacted plowpan or hardpan layer below the tilled topsoil layer negatively impacts the roots of plants, with significant consequences. While most roots occur closer to the surface where more nutrients are available, roots deeper in the profile can reach stored water in uncompacted soil (Dexter 1988). In compacted soils with high penetration resistance, roots are confined to the upper layer of soil and then grow sideways rather than downward; this reduces the volume of soil from which water and nutrients can be pulled (Figure 8) (Rosolem et al. 2002). Consequently, this region becomes depleted of water more rapidly, and since soil strength increases as moisture decreases, this creates a negative feedback loop. It becomes more problematic during drought due to reduced total pore space for water storage (Bushamuka and Zobel 1998). The topsoil's supply of nutrients, already reduced because of runoff or leaching, can drop below what is sufficient (Boone 1988; Soane and Ouwerkerk 1995).

When the hydrostatic pressure exerted by the root tip is inadequate to penetrate a compacted soil layer, roots tend to deflect sideways to seek a pathway of lesser resistance rather than continuing downward through the resistant layer (Bengough and Mullins 1990; Hamza and Anderson 2005). These roots may resume growing downward if they encounter a crack or pore (Dexter 1988). However, roots encountering high penetration resistance must use more energy to overcome that resistance (Colombi et al. 2017). As the plant struggles to penetrate the resistant layer, it undergoes physical changes to its roots; this, combined with the extra energy expenditure, leads to reduced growth and elongation, deformation, and damage (Materechera et al. 1991; Nawaz et al. 2013). The thickening of the root is a typical result of increased soil strength, with studies finding that every plant species evaluated undergoes this response (Materechera et al. 1991; Colombi et al. 2017). Root thickening strengthens the root, allowing for the increased pressure necessary to push into a resistant soil and to resist buckling (Materechera et al. 1992).

Figure 7. Rilling on the downhill side of a compacted raspberry row. (Figure credit: Deirdre Griffin-LaHue.)

Figure 8. Spinach root growth truncated by compaction. (Figure credit: Gabriel LaHue.)

Studies have shown that root growth in dicots, which tend to have larger diameter roots, is less affected by compaction than in fibrous-rooted monocots. Chen and Weil (2010) compared forage radish, rape, and rye and found that the radish, a dicot, was the least impeded by compaction; rye, on the other hand, experienced the most root growth limitation. Materechera et al. (1991) grew monocots and dicots in a sandy soil in a compression chamber to simulate high soil strength. Dicots showed a greater ability than monocots to elongate in the sandy medium; they suggest that this is due to the ability of dicots to apply greater axial growth pressure. Hence, species with a taproot are more suitable for “biodrilling” to remediate compaction (Figure 9, bottom photo). An increase in both the deposition of mucilage and the sloughing of root cap cells from root tips has been observed in plants growing in compacted soils; these act as a lubricant for roots as they grow (Iijima et al. 2000). These processes also exact an energy cost to the plant.

Many studies have demonstrated that yield is reduced in compacted soils (Ishaq et al. 2001; Hamza and Anderson 2005; Schjønning et al. 2015; Shah et al. 2017; Sinton et al. 2022). There is some evidence that subsoil compaction may not impact yield if roots can obtain needed nutrients and water in the surface soil layer (Rosolem and Takahashi 1998). As such, the yield reduction from soil compaction may be particularly severe in rainfed production and under drought conditions. However, the many other negative impacts of compaction are likely to occur across a wide range of production systems.

Managing Compaction with Implements

Given that the ultimate ramifications of soil compaction can include yield loss, soil erosion, and surface water pollution, land management practices must be developed and employed to combat the problem. Some strategies are designed to minimize compaction, while others are used to remediate existing compaction; however, all have limitations (Table 1).

Compaction can be partially avoided by limiting loads, using lower tire pressures, and avoiding all traffic while the soil is wet (Hamza and Anderson 2005). Other strategies include controlled traffic farming, which reduces traffic in beds by placing all wheeled traffic on the same tracks for all operations, year after year. Tire tracks will be compacted, while the beds in between the tire tracks will remain loose and porous. The controlled traffic system addresses many problems associated with compacted fields, although it does not eliminate them. Also, compaction can spread to areas adjacent to tire tracks over time (Håkansson and Reeder 1994). Some have suggested that combining more operations over fewer passes could reduce compaction (Hamza and Anderson 2005), while others have blamed machines designed for multiple tasks, such as combine harvesters, for increased loads (Shah et al. 2017).

Some remediation of soil compaction may occur through natural processes. In expanding clay soils, the natural shrink or swell cycles will lead to some recovery from compaction damage (Spoor 2006). Freeze and thaw cycles and faunal-driven processes, such as burrowing by earthworms and rodents, also relieve compaction (Webb 2002; Drewry 2006; Gregory et al. 2007). However, these factors generally only influence the top layers of the profile, and the processes may take decades to centuries when compaction is severe (Webb 2002).

Table 1. Pros and cons of different strategies to prevent and reduce soil compaction.

Strategy	Purpose	Pros	Cons
Controlled traffic	Prevent compaction by confining vehicle compaction to designated areas.	Prevent negative effects of vehicle compaction in cropped areas.	Requires planning to maintain tractor pathways. Tractors and implements with different tire spacing or widths can be challenging to accommodate.
Soil fauna (e.g., earthworms)	Enhancing and supporting soil fauna promotes biopores in soils.	Long-term and natural soil health.	May take a long time to establish. Agricultural practices are often destructive to large soil fauna.
Cover cropping	Roots create biopores in soil; taproots may biodrill through compacted layers.	Addition of organic matter supports soil structure; long-term and natural soil health.	Limits to biodrilling effect—may not penetrate heavily compacted areas; several years of cover cropping are likely necessary to see effects.
Tillage (e.g., 4 to 8 inches [10 to 20 cm])	Reduce compaction in surface.	Most roots and nutrient exchange occur in surface layers. Reducing compaction at surface can enhance plant growth.	Recompaction is likely without changes in practices. Can destroy soil structure and promote the decomposition of organic matter.
Deep plowing (e.g., 1 to 2 feet [30 to 60 cm])	Reduce compaction at depth.	Quickly alleviates compaction.	Recompaction is likely. High fuel and horsepower requirement. Can contribute to compaction/plow pan.
Deep ripping, 1.5 ft (45 cm) or greater; aka vertical tilling, subsoiling	Reduce compaction at depth.	Quickly alleviates compaction.	Recompaction is likely. High fuel and horsepower requirement.

Tillage practices remain the most frequently employed tactics for ameliorating the effects of compaction. Compaction of the top layers may be remedied by normal tillage, but as noted above, compaction may run well below 30 cm—in these situations, deep tillage is required. Unfortunately, deep tillage requires expensive equipment, time, and fuel (Spoor 2006). Deep tillage practices (also called deep ripping or subsoiling) require consideration of moisture levels as the soil must be friable enough to break as the implement passes through (Batey 2009). Subsoiling effectively loosens compacted subsoil and improves penetration resistance in the plow pan (Olesen and Munkholm 2007). Van-Camp et al. (2004) noted that deep ripping is preferable to deep plowing because it is less likely to promote organic matter decomposition. Some studies have reported improvements in crop yield with deep tillage (e.g., Dexter 1991; Hamza and Anderson 2003; Mochizuki et al. 2007), though these benefits often disappear after a couple of years, and many studies have reported yield declines with time after deep tillage (Dexter 1991; Munkholm et al. 2005; Mochizuki et al. 2007). This is likely connected to a soil's vulnerability to recompaction after deep tillage (Munkholm et al. 2005). Given this short-lived impact and the fuel and labor costs associated with deep tillage, deep soil loosening may be best reserved for severe cases of compaction; otherwise, reducing traffic and adopting management practices favorable to the formation and maintenance of biopores may be more effective strategies (Munkholm et al. 2005).

Cover Crops to Alleviate Compaction

Cover crops have many benefits for soil health, including increasing or maintaining soil organic matter, improving water retention, controlling erosion, and suppressing weeds (Wilson et al. 1982). Certain cover crops can "biologically drill," or penetrate a compacted layer, thereby creating macropores through which plant roots, water, and air can move (Figure 9; Cresswell and Kirkegaard 1995). Photographic evidence indicates that roots of plants sown after deep-rooted cover crops can grow through the channels made by previous cover crop roots (Williams and Weil 2004). Cover crop roots also affect the overall amount of pore space and the geometry of pore spaces by facilitating soil faunal activity (Dabney 1998; Pulido-Moncada et al. 2020). There is still uncertainty around the time required for cover crops to relieve compaction, which cover crops are the most effective in specific situations, and at what level of compaction are cover crops effective for remediation.

Figure 9. Fava bean taproot (top photo) and tillage radish (bottom photo) can be planted to "biodrill" through a compacted soil layer. (Figure credit: Justin Maltry.)

There is little information, or occasionally conflicting information, around which types of cover crops, generally, and which species and cultivars, more specifically, are best suited to penetrate compacted soil. There is a significant disparity between different plants' abilities to do so, which is tied to both genotype and phenotype (Colombi et al. 2017). It has been suggested that perennial plants are best suited for compaction relief because they tend to have roots in the ground exploring the subsoil for many years (Cresswell and Kirkegaard 1995; Gentile et al. 2003). However, given a farm's equipment and markets, perennial cover crops may not be suitable. Many researchers have found that taprooted options have performed better than those with small, fibrous root systems in penetrating compacted soil layers (Chen and Weil 2010). This is because thicker roots are more resistant to buckling and deflection than smaller roots and experience relatively less friction (Chen and Weil 2010). Another possible explanation is that thicker roots exert more pressure, though some studies have found that dicots do not exert more axial root pressure than monocots (Clark and Barraclough 1999; Chen and Weil 2010). Brassica crops, especially fodder radish (*Raphanus sativus*), have been shown to have a superior ability to penetrate compacted soils when compared with grasses and even other brassicas (Chen and Weil 2010; Abdollahi et al. 2014), though this ability can be compromised by low overall planting density (Pulido-Moncada et al. 2020). Legumes, such as fava bean, pea, lucerne, and sunn hemp, are also commonly used as cover crops in compacted soils (Materechera et al. 1992; Calonego et al. 2017).

Despite the focus on dicots with taproots, grasses are also well suited to remediate compaction due to their pervasive root systems that explore a significant volume of soil and leave behind numerous pores (Calonego et al. 2017). A proportionally higher number of thin roots penetrate highly compacted soil than thicker ones (Whiteley and Dexter 1984). For example, the grasses *Pennisetum americanum* (pearl millet) and *Sorghum bicolor* (guinea sorghum) had a higher root length density under the layer of compaction than tap-rooted species (Garcia et al. 2013; Calonego et al. 2017).

While there is debate on whether fibrous roots or taproots are more effective, there is nonetheless considerable evidence that cover crops contribute to compaction remediation. In a 10-year experiment that compared the effects of tillage with fodder radish, researchers found that five consecutive years of radish plantings significantly improved penetration resistance and the pore network, but a decade of tillage had little impact on overall pore space (Abdollahi et al. 2014; Abdollahi and Munkholm 2014). Chicory (*Cichorium intybus*, aster family) and lucerne (*Medicago sativa*, legume family) have also been shown to improve porosity, even after only a single crop year, and may outperform radish over a short time frame (Pulido-Moncada et al. 2020). Chen and Weil (2011) indicated that channels left by a previous cover crop allowed the subsequent maize crop to better access water and thereby increase its growth and yield, though, in this one-year experiment, they found no evidence that the radish, rapeseed, and rye cover crops changed penetration resistance or bulk density. Like the yield increase in maize, Williams and Weil (2004) found that soybean yields improved after a cover crop of forage radish and rye compared to treatments without a cover crop. Remarkably, using a "minirhizotron" camera, they could capture images of soybean roots growing in the same channels the previous cover crop plants left. A longer-term study determined that while tillage's benefits start to backslide within a year or two, sunn hemp increased porosity, improved soil structure, and increased soybean yield longer-term. Cover crops require a longer time frame than tillage for the benefits to be fully realized. This delay can be difficult to navigate since a farmer can immediately see the effects of tillage on compacted layers, while cover cropping may require a long-term overhaul of management practices.

Not all studies support the potential of cover crops to remediate soil compaction, and some other studies have shown no significant effects, or even adverse effects, from cover crop use. In a three-year study, Bryant et al. (2020) found that growing a cereal rye cover crop instead of subsoiling led to equivalent yields, while radish led to reduced yield. They also calculated that the greater input costs for cover crops dramatically diminished the net return. Another short (one-year) study showed that when rye and triticale were used as a cover crop, the following soybean crop suffered reduced yields, and soil structure was unimproved (Cresswell and Kirkegaard 1995). Acuña and Villamil (2014) found that though canola penetrated the compacted layer, there were no improvements to soil structure, porosity, and saturated hydraulic conductivity. These conflicting results suggest that using cover crops to ameliorate compaction requires a long-term commitment and that careful attention to cover crop selection, growing practices, and economic feasibility are essential.

Conclusions

While scientists and farmers acknowledge the need to improve land management practices, there is a trend toward increasing soil compaction. The consequences of compaction may be severe, including reduced pore space, decreased infiltration, greater runoff, more significant potential for surface water pollution, diminished soil function, and reduced crop yield. While compaction in the top 30–40 cm can be more easily managed with tillage, subsoil compaction is expensive and difficult to resolve with tillage. Cover crops, especially those with thick taproots, may be able to help remediate soil compaction when managed appropriately, though benefits would be maximized when used in conjunction with other land management practices such as controlled traffic systems.

Acknowledgments

Support was provided through a Pierce County Floodplains by Design Project grant, managed by Pierce Conservation District (PCD).

References

Abdollahi, L., and L.J. Munkholm. 2014. Tillage System and Cover Crop Effects on Soil Quality: I. Chemical, Mechanical, and Biological Properties. *Soil Science Society of America Journal* 78: 262–270.

Abdollahi, L., L.J. Munkholm, and A. Garbout. 2014. Tillage System and Cover Crop Effects on Soil Quality: II. Pore Characteristics. *Soil Science Society of America Journal* 78: 271–279.

Acuña, J.C.M., and M.B. Villamil. 2014. Short-Term Effects of Cover Crops and Compaction on Soil Properties and Soybean Production in Illinois. *Agronomy Journal* 106: 860–870.

van den Akker, J.J.H. 2008. Soil Compaction. In *Environmental Assessment of Soil for Monitoring: Volume I Indicators & Criteria*, Huber, S., Prokop, G., Arrouays, D., Banko, G., Bispo, A., Jones, R. J. A., Kibblewhite, M. G., Lexer, W., M€oller, A., Rickson, R. J., Shishkov, T., Stephens, M., Toth, G., Akker, J. J. H., Varallyay, G., Verheijen, F. G. A., Jones, A. R. (eds.), 107–124. Office for the Official Publications of the European Communities.

Alakukku, L., P. Weisskopf, W.C. Chamen, F.G. Tijink, J. Linden, S. Pires, C. Sommer, and G. Spoor. 2003. Prevention Strategies for Field Traffic-Induced Subsoil Compaction: A Review: Part 1. Machine/Soil Interactions. *Soil & Tillage Research* 73: 145–160.

Ball, B.C., I. Crichton, and G.W. Horgan. 2008. Dynamics of Upward and Downward N_2O and CO_2 Fluxes in Ploughed or No-Tilled Soils in Relation to Water-Filled Pore Space, Compaction and Crop Presence. *Soil & Tillage Research* 101: 20–30.

Batey, T. 2009. Soil Compaction and Soil Management—A Review. *Soil Use and Management* 25: 335–345.

Bengough, A.G., and C.E. Mullins. 1990. Mechanical Impedance to Root Growth: A Review of Experimental Techniques and Root Growth Responses. *Journal of Soil Science* 41: 341–358.

Boone, F.R. 1988. Weather and Other Environmental Factors Influencing Crop Responses to Tillage and Traffic. *Soil & Tillage Research* 11: 283–324.

Brady, N.C., and R.R. Weil. 2002. *The Nature and Property of Soils* 13th ed. Pearson Prentice Hall.

Bryant, C.J., L.J. Krutz, D.B. Reynolds, M.A. Locke, B.R. Golden, T. Irby, R.W. Steinriede, G.D. Spencer, B.E. Mills, and C.W. Wood. 2020. Conservation Soybean Production Systems in the Mid-Southern USA: II. *Crop, Forage & Turfgrass Management* 6.

Bushamuka, V.N., and R.W. Zobel. 1998. Differential Genotypic and Root Type Penetration of Compacted Soil Layers. *Crop Science* 38: 776–781.

Calonego, J.C., J.P.A. Raphael, J.P.G. Rigon, L. de Oliveira Neto, and C.A. Rosolem. 2017. Soil Compaction Management and Soybean Yields with Cover Crops Under No-Till and Occasional Chiseling. *European Journal of Agronomy* 85: 31–37.

CCIL. 2021. Moisture-Density Relationship of Soils Using 2.5 kg Rammer and 305 mm Drop. LS-706 R33.

Chen, G., and R.R. Weil. 2010. Penetration of Cover Crop Roots Through Compacted Soils. *Plant and Soil* 331: 31–43.

Chen, G., and R.R. Weil. 2011. Root Growth and Yield of Maize as Affected by Soil Compaction and Cover Crops. *Soil & Tillage Research* 117: 17–27.

Clark, L.J., and P.B. Barraclough. 1999. Do Dicotyledons Generate Greater Maximum Axial Root Growth Pressures Than Monocotyledons? *Journal of Experimental Botany* 50: 1263–1266.

Colombi, T., N. Kirchgessner, A. Walter, and T. Keller. 2017. Root Tip Shape Governs Root Elongation Rate Under Increased Soil Strength. *Plant Physiology* 174: 2289–2301.

Cresswell, H.P., and J.A. Kirkegaard. 1995. Subsoil Amelioration by Plant-Roots—The Process and the Evidence. *Australian Journal of Soil Research* 33: 221–239.

Dabney, S.M. 1998. Cover Crop Impacts on Watershed Hydrology. *Journal of Soil and Water Conservation* 53: 207–213.

Dexter, A.R. 1988. Advances in Characterization of Soil Structure. *Soil & Tillage Research* 11: 199–238.

Dexter, A.R. 1991. Amelioration of Soil by Natural Processes. *Soil & Tillage Research* 20: 87–100.

Díaz-Zorita, M., and G.A. Grosso. 2000. Effect of Soil Texture, Organic Carbon and Water Retention on the Compactability of Soils from the Argentinean Pampas. *Soil and Tillage Research* 54: 121–126.

Drewry, J.J. 2006. Natural Recovery of Soil Physical Properties from Treading Damage of Pastoral Soils in New Zealand and Australia: A Review. *Agriculture, Ecosystems & Environment* 114: 159–169.

Fritz, V.A., R. Allmaras, F. Pfleger, and D. Davis. 1995. Oat Residue and Soil Compaction Influences on Common Root Rot (*Aphanomyces euteiches*) of Peas in a Fine-Textured Soil. *Plant and Soil* 171: 235–244.

Fukao, T., and J. Bailey-Serres. 2004. Plant Responses to Hypoxia—Is Survival a Balancing Act? *Trends in Plant Science* 9: 449–456.

Garcia, R.A., Y. Li, and C.A. Rosolem. 2013. Soil Organic Matter and Physical Attributes Affected by Crop Rotation Under No-Till. *Soil Science Society of America Journal* 77: 1724–1731.

Gentile, R., D. Martino, and M. Entz. 2003. Root Characterization of Three Forage Species Grown in Southwestern Uruguay. *Canadian Journal of Plant Science* 83: 785–788.

Gregory, A.S., C. Watts, W. Whalley, H. Kuan, B. Griffiths, P. Hallett, and A. Whitmore. 2007. Physical Resilience of Soil to Field Compaction and the Interactions with Plant Growth and Microbial Community Structure. *European Journal of Soil Science* 58: 1221–1232.

Håkansson, I., and J. Lipiec. 2000. A Review of the Usefulness of Relative Bulk Density Values in Studies of Soil Structure and Compaction. *Soil & Tillage Research* 53: 71–85.

Håkansson, I., and R.C. Reeder. 1994. Subsoil Compaction by Vehicles with High Axle Load—Extent, Persistence and Crop Response. *Soil & Tillage Research* 29: 277–304.

Hamza, M.A., and W.K. Anderson. 2003. Responses of Soil Properties and Grain Yields to Deep Ripping and Gypsum Application in a Compacted Loamy Sand Soil Contrasted with a Sandy Clay Loam Soil in Western Australia. *Australian Journal of Agricultural Research* 54: 273–282.

Hamza, M.A., and W.K. Anderson. 2005. Soil Compaction in Cropping Systems. *Soil & Tillage Research* 82: 121–145.

Horn, R., H. Domżżał, A. Słowińska-Jurkiewicz, and C. Ouwerkerk. 1995. Soil Compaction Processes and Their Effects on the Structure of Arable Soils and the Environment. *Soil & Tillage Research* 35: 23–36.

Iijima, M., B. Griffiths, and A.G. Bengough. 2000. Sloughing of Cap Cells and Carbon Exudation from Maize Seedling Roots in Compacted Sand. *The New Phytologist* 145: 477–482.

Ishaq, M., A. Hassan, M. Saeed, M. Ibrahim, and R. Lal. 2001. Subsoil Compaction Effects on Crops in Punjab, Pakistan: I. Soil Physical Properties and Crop Yield. *Soil & Tillage Research* 59: 57–65.

Jorgensen, P.R., L.D. McKay, and N.H. Spliid. 1998. Evaluation of Chloride and Pesticide Transport in a Fractured Clayey Till Using Large Undisturbed Columns and Numerical Modeling. *Water Resources Research* 34: 539–553.

Kooistra, M.J., and N.K. Tovey. 1994. Effects of Compaction on Soil Microstructure. In *Soil Compaction in Crop Production*, Soane, B.D., Ouwerkerk, C. (eds.), 91–111. Elsevier Science & Technology.

Materechera, S.A., A.M. Alston, J.M. Kirby, and A.R. Dexter. 1992. Influence of Root Diameter on the Penetration of Seminal Roots into a Compacted Subsoil. *Plant and Soil* 144: 297–303.

Materechera, S.A., A. Dexter, and A. Alston. 1991. Penetration of Very Strong Soils by Seedling Roots of Different Plant Species. *Plant and Soil* 135: 31–41.

Mochizuki, M.J., A. Rangarajan, R.R. Bellinder, T. Bjorkman, and H.M. Es. 2007. Overcoming Compaction Limitations on Cabbage Growth and Yield in the Transition to Reduced Tillage. *HortScience* 42: 1690–1694.

Munkholm, L.J., P. Schjønning, M.H. Jorgensen, and K. Thorup-Kristensen, 2005. Mitigation of Subsoil Recompaction by Light Traffic and On-Land Ploughing: II.: Root and Yield Response. *Soil & Tillage Research* 80: 159–170.

Nawaz, M.F., G. Bourrié, and F. Trolard. 2013. Soil Compaction Impact and Modelling. A Review. *Agronomy for Sustainable Development* 33: 291–309.

Olesen, J.E., and L.J. Munkholm. 2007. Subsoil Loosening in a Crop Rotation for Organic Farming Eliminated Plough Pan with Mixed Effects on Crop Yield. *Soil & Tillage Research* 94: 376–385.

Pagliai, M., N. Vignozzi, and S. Pellegrini. 2004. Soil Structure and the Effect of Management Practices. *Soil & Tillage Research* 79: 131–143.

Pulido-Moncada, M., S. Katuwal, L. Ren, W. Cornelis, and L. Munkholm. 2020. Impact of Potential Bio-Subsoilers on Pore Network of a Severely Compacted Subsoil. *Geoderma* 363: 114154.

Pupin, B., O.D.S. Freddi, and E. Nahas. 2009. Microbial Alterations of the Soil Influenced by Induced Compaction. *Revista Brasileira de Ciência Do Solo* 33: 1207–1213.

Quirk, J.P., and C.R. Panabokke. 1962. Incipient Failure of Soil Aggregates. *Journal of Soil Science* 13: 60–70.

Rosolem, C.A., J.S.S. Foloni, and C.S. Tiritan. 2002. Root Growth and Nutrient Accumulation in Cover Crops as Affected by Soil Compaction. *Soil & Tillage Research* 65: 109–115.

Rosolem, C.A., and M. Takahashi. 1998. Soil Compaction and Soybean Root Growth. In *Proceedings of the 5th Symposium of the International Society of Root Research*, Box, J.E. (ed.), 295–304.

Schjønning, P., J.J.H. van den Akker, T. Keller, M.H. Greve, M. Lamandé, A. Simojoki, M. Stettler, J. Arvidsson, and H. Breuning-Madsen. 2015. Driver-Pressure-State-Impact-Response (DPSIR) Analysis and Risk Assessment for Soil Compaction—A European Perspective. *Advances in Agronomy* 183–237. Elsevier.

Shah, A.N., M. Tanveer, B. Shahzad, G. Yang, S. Fahad, S. Ali, M.A. Bukhari, S.A. Tung, A. Hafeez, and B. Souliyanonh. 2017. Soil Compaction Effects on Soil Health and Crop Productivity: An Overview. *Environmental Science and Pollution Research International* 24: 10056–10067.

Sinton, S.M., R.E. Falloon, P.D. Jamieson, E.D. Meenken, F.A. Shah, H.E. Brown, S.J. Dellow, A.J. Michel, and J.D. Fletcher. 2022. Yield Depression in New Zealand Potato Crops Associated with Soil Compaction and Soil-Borne Diseases. *American Journal of Potato Research* 99: 160–173.

Soane, B.D. 1990. The Role of Organic Matter in Soil Compactibility: A Review of Some Practical Aspects. *Soil and Tillage Research* 16: 179–201.

Soane, G.C., R. Godwin, M. Marks, and G. Spoor. 1987. Crop and Soil Response to Subsoil Loosening, Deep Incorporation of Phosphorus and Potassium Fertilizer and Subsequent Soil Management on a Range of Soil Types. 2. Soil Structural Conditions. *Soil Use and Management* 3: 123–130.

Soane, B.D., and C. Ouwerkerk. 1995. Implications of Soil Compaction in Crop Production for the Quality of the Environment. *Soil & Tillage Research* 35: 5–22.

Spoor, G. 2006. Alleviation of Soil Compaction: Requirements, Equipment and Techniques. *Soil Use and Management* 22: 113–122.

Van-Camp, L., B. Bujarrabal, A.-R. Gentile, R.J.A. Jones, L. Montanarella, C. Olazabal, and S.-K. Selvaradjou. 2004. Reports of the Technical Working Groups Established Under the Thematic Strategy for Soil Protection. EUR 21319 EN/6: 872.

Vogel, T., H.H. Gerke, R. Zhang, and M.T. Genuchten. 2000. Modeling Flow and Transport in a Two-Dimensional Dual-Permeability System with Spatially Variable Hydraulic Properties. *Journal of Hydrology* (Amsterdam) 238: 78–89.

Webb, R.H. 2002. Recovery of Severely Compacted Soils in the Mojave Desert. *Arid Land Research and Management* 16: 291–305.

Whiteley, G.M., and A.R. Dexter. 1984. The Behaviour of Roots Encountering Cracks in Soil: I.: Experimental Methods and Results. *Plant and Soil* 77: 141–149.

Williams, S.M., and R.R. Weil. 2004. Crop Cover Root Channels May Alleviate Soil Compaction Effects on Soybean Crop. *Soil Science Society of America Journal* 68: 1403–1409.

Wilson, G.F., R. Lal, and B.N. Okigbo. 1982. Effects of Cover Crops on Soil Structure and on Yield of Subsequent Arable Crops Grown Under Strip Tillage on an Eroded Alfisol. *Soil and Tillage Research* 2: 233–250.

Wolfe, D.W., D.T. Topoleski, N.A. Gundersheim, and B.A. Ingall. 1995. Growth and Yield Sensitivity of Four Vegetable Crops to Soil Compaction. *Journal of the American Society for Horticultural Science* 120: 956–963.

By
Justin Maltry, Adjunct Faculty, Puyallup Research and Extension Center,
Washington State University
Douglas Collins, Professor and Extension Specialist, Agriculture and Natural Resources,
Washington State University
Gabriel LaHue, Assistant Professor Soil Science, Crop and Soil Sciences,
Washington State University
Anand D. Jayakaran, Professor and Green Stormwater Infrastructure Specialist,
Agriculture and Natural Resources, Washington State University

Cover photo credit: Douglas Collins.

WSU PEER REVIEWED

FS396E

WASHINGTON STATE UNIVERSITY
EXTENSION