doi:10.2489/jswc.72.1.10A

FEATURE

Fluffy soil syndrome: When tilled soil does not settle

Aaron Lee M. Daigh and Jodi DeJong-Hughes

Soil tillage is one of the most common management practices in any crop production system across the world. Over the centuries, tillage tools have evolved from simple tools for preparing a soft, weed-free area for easy planting to sophisticated implements for managing high levels of crop residues, facilitating the warming of frigid soils, and incorporating some forms of fertilizers. On one hand, a producer who tills can increase their potential for a high yielding crop during the upcoming growing season. On the other hand, tillage can innately induce some well-known challenges (Triplett and Dick 2008):

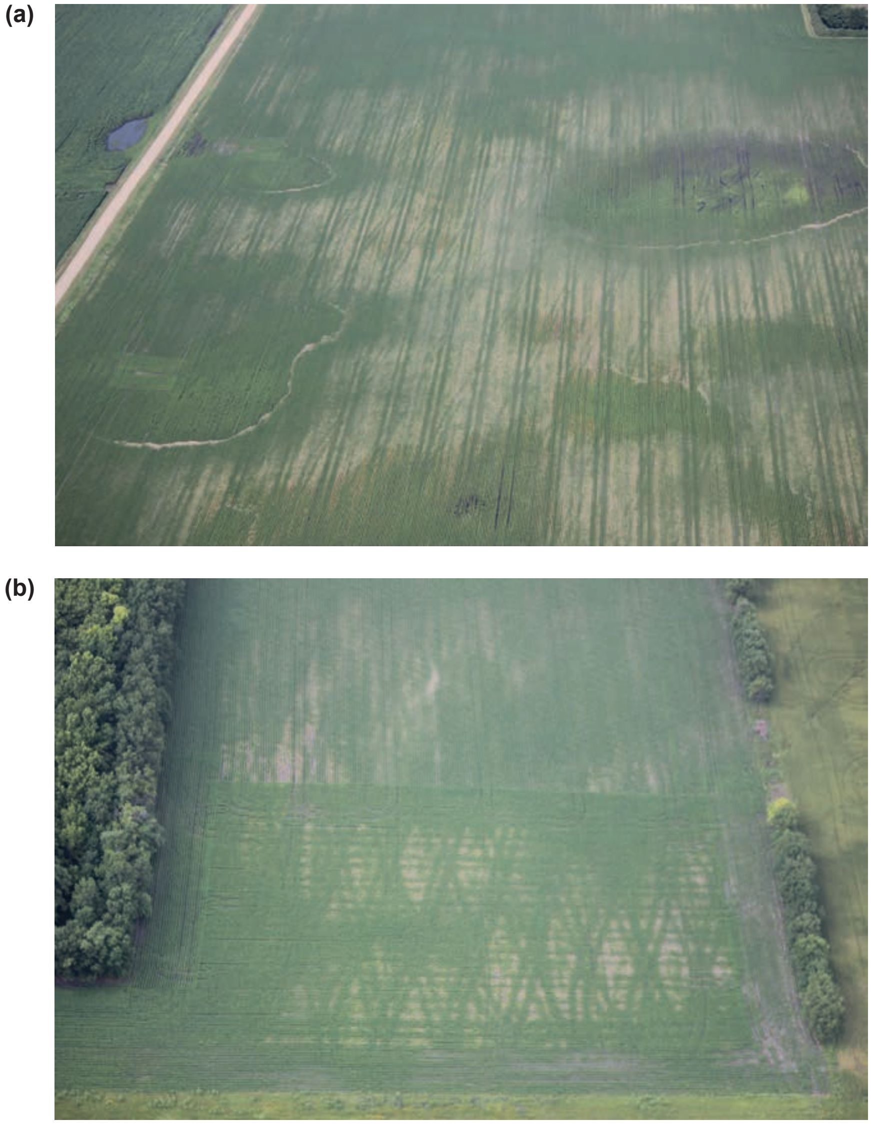
1. Risk of increasing wind and water erosion
2. Accelerating the oxidation of soil organic matter
3. Limiting the formation of stable soil aggregates
4. Risk of compacting the subsoil just below the depth of tillage

Many more advantages and disadvantages associated with soil tillage exist, but this list includes some of the more commonly discussed issues among agronomists in the US upper Midwest and northern Great Plains regions. However, agronomists rarely, if ever, consider the risk for tillage to create inadequate particle-to-particle contact, and therefore, poor seed-to-soil (or root-to-soil) contact.

Since the winter that bridged 2014 and 2015, much of the US upper Midwest and northern Great Plains regions have experienced relatively dry winters with little snow cover and few precipitation events occurring between fall primary tillage and spring planting of crops. These dry winters and springs limit the amount of soil settling that would typically occur in the tilled depth of soil. Producers and extension specialists have begun to notice unique patterns of poor crop stands in some fields where healthy plants tend to grow only in the compacted tractor-tire pathways and along the edges of low-lying depressions where plants did not drown (figure 1). This syndrome, which we have come to refer as fluffy soil syndrome (FSS) at extension field days with crop producers, occurs when tilled soil does not settle over the winter and spring months, resulting in crops suffering from inadequate soil particle-to-particle contact.

Figure 1

Tilled fields in western Minnesota with (a and b) visual symptoms of poor particle-to-particle contact effects on crop performance (fluffy soil syndrome [FSS]). These aerial photographs were taken in July of 2015 and show healthy plant growth within compacted tire pathways and poor plant growth between tire pathways. The areas along the low-lying depressions likely provided wetting and drying cycles that alleviated some of the FSS. The effect of FSS on crop performance can be difficult for producers to see in their fields from the roads, but is unmistakable from aerial images.



Aaron Lee M. Daigh is an assistant professor of Soil Physics in the Soil Science Department at North Dakota State University, Fargo, North Dakota, and **Jodi DeJong-Hughes** is a crop Extension educator at the University of Minnesota Mid-Central Research and Outreach Center in Willmar, Minnesota.

FLUFFY SOIL SYNDROME

Causes of Fluffy Soil Syndrome: Coupling of Management Practices and Soil Physical Processes. Fluffy soil syndrome is the direct result of soil tillage followed by the absence, or lack, of wetting/drying or freezing/thawing cycles. Tillage practices used to alleviate subsoil compaction (i.e., in-line subsoiling without crop residue incorporation) or to size crop residues into small pieces (i.e., shallow vertical tillage) will not contribute to FSS. Only tillage practices that aggressively loosen the soil, within the depths where seeds are subsequently placed and where seedling root systems first develop, are expected to lead to FSS. Such tillage practices may include implements that incorporate 70% or more of crop residues (e.g., moldboard plows, chisel plows, disc harrows, and cultivators) into the soil by either inverting or rigorously tilling the soil.

In these types of tillage systems, the implement's shanks, shovels, spikes, disks or coulters induce shear stresses on the soil. This causes the soil to deform, rupture, and fracture as the soil strains and the stresses exceed the soil's strength. Once soil particles and small aggregates initially dislodge and "fluff," they will undergo some degree of immediate settling due to gravity and the weight of other tilled particles falling on top of other particles (Horton et al. 2016). After this immediate phase of post-tillage settling due to gravity, soil properties will have been significantly altered from their pre-tilled state and will persist until wetting/drying or freezing/thawing cycles cause soil particles to settle further. Significant changes in physical properties include the following:

1. Decreased soil bulk density (thus, an increase in total soil porosity)
2. Rearrangement of soil pore networks, architecture, and tortuosity
3. Reduced number of contact points among mineral and aggregate surfaces
4. Increased distance between these contact points
5. Decreased hydraulic conductivities at low soil water contents
6. Increased transfer of soil gasses
7. Increased occurrence of evaporation within the subsurface
8. Decreased conduction and convection of soil heat

However, soil tillage only creates the initial conditions required for FSS by altering the soil's physical properties. A tilled soil would need to maintain its "loosened" properties throughout the months/weeks before and after planting for FSS to occur. During normal winter and spring months in the US upper Midwest and northern Great Plains regions, soils experience repeated wetting/drying and freezing/thawing cycles between the first fall primary tillage and spring planting of a crop (figure 2).

Soil drying and freezing are similar processes in some regards. Ice nucleation and formation during freezing occurs first in large pores, effectively dropping the soil water potential energy and creating a hydraulic gradient in the direction of the ice formation. This flow of liquid water toward the ice desiccates neighboring smaller pores, causing shrinkage on the bulk soil (Hamilton 1966; Dagesse 2016). However, if the freezing soil contains more than 85% water-filled pore space, the expanding ice will cause the bulk soil to also expand (Hamilton 1966). During the freezing or drying processes, small soil particles within the water will accumulate near the contact points between larger particles or soil aggregates. This accumulation of particles with charged surfaces at the contact points can irreversibly cement the contact points together and stabilize these points as water films progressively thin (Horton et al. 2016). Subsequent thawing is therefore also similar in many regards to soil wetting. As the ice melts, the soil water potential energy increases and the hydraulic gradient reverses, causing the desiccated neighboring pores to then expand in shrink-swell soils. This cycling of freezing/thawing and shrinking/swelling repeats numerous times even under a snow-covered soil, causing near-continuous changes to soil aggregation and strength and thus supplying the forces needed for soil settling (figure 2; Edwards et al. 2007; Wang et al. 2012).

If the tilled, or "fluffed," soil does not settle, but persists into and beyond spring planting, properties of the loosened soil will limit flows and supply rates of liquid water and dissolved nutrients to the seed/seedling while also maximizing water vapor transport to the atmosphere and potential for desiccation. Some research reports indicate seeds obtain most of their water via the transfer of water vapor and not liquid water flows (Wuest 2002, 2007). However, soils vulnerable to FSS have very high porosities in the tilled zone making them more prone to diffusive, convective, and dispersive gas transport to the atmosphere (Parlange et al. 1998; Grifoll et al. 2005). In order for water vapors to meet seed/seedling root water demands, an adequate supply of evaporating liquid water from either the tilled mineral surfaces or from underlying non-tilled soil horizons must be available to replace vapor losses to the atmosphere at the time the seed is planted (Bouaziz and Bruckler 1989). Otherwise, desiccation will occur. This may be particularly challenging in a low density, tilled soil that is rapidly accumulating heat (Nassar and Horton 1997). Additionally, the seed may not be able to imbibe the water vapor at a high enough rate due to the seed's physiology even if adequate supply rates of water vapor to the seed exist (Jordan 1983). The seed/seedling may also become prone to disease since a partially wet (slow water imbibition), slowly germinating seed in a soil experiencing rapid accumulation of heat presents an environment for plant pathogens to target.

In the end, the effect of low water supply rates on the seed/seedling's ability to maintain hydration, grow, and survive is what governs FSS in producer fields. The absence of FSS in tire pathways and in low laying areas is due to the ability for the compacted, moist soil to supply adequate rates of water flow to the seed/seedling roots. Interestingly, we have also observed healthy plants growing in straight lines where no tire pathway is evident from the soil surface (figure 1). However, these straight lines occur in patterns that match the trafficking of other agricultural equipment prior to soil tillage. In these locations, a compacted subsurface from previous tire traffic is likely supplying liquid water flows from deep in the soil profile up to the tilled depths where water vapor transport may be adequately supplied for good seed germination and subsequent plant growth.

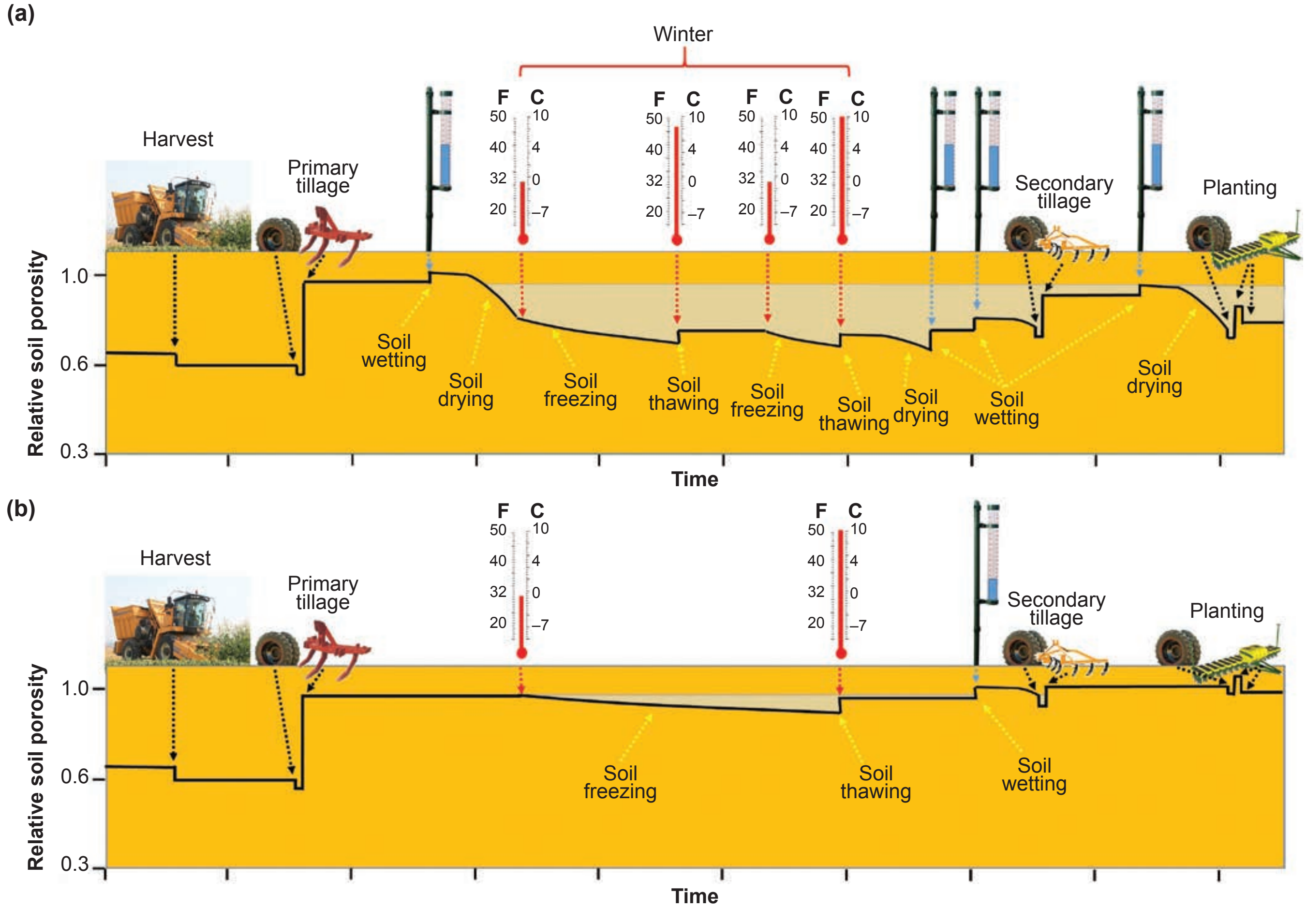
Consequences on Seed Performance and Soil Erosion Potential. The consequence of FSS is oftentimes difficult for producers to see from the roads bordering their fields, but is unmistakable from aerial photos (figure 1). Since nearly all nonirrigated and adequately drained agricultural soils remain only partially saturated throughout the growing season, liquid water flows are restricted to (1) small pores and (2) water films along particle surfaces and their contact points with neighboring particles or aggregates (Daigh et al. 2014a, 2014b; Horton et al. 2016; Schott et al. 2017). Therefore, these contact points control a large portion of the water, nutrient, gas, and heat flows in the soil matrix and to the seed/seedling roots (Carminati et al. 2008). A lack of contact points limits water and nutrient flows to the seed while maximizing gas exchange and thermal insulation, whereas an abundance of contacts limits gas exchange and thermal insulation while maximizing water and nutrient flows to the seed. A soil low in particle-to-particle contacts and under dry conditions will cause cell-water stress and the potential for plant stunting, wilting, and possibly death. Additionally, the low soil strength associated with few contact points coupled with poor crop stands can leave soils exposed and vulnerable to wind erosion extending from the fallow season and well into the growing season (figure 1).

LANDS PROSPECTIVELY VULNERABLE TO FLUFFY SOIL SYNDROME

The occurrence of FSS will vary based on the tillage practice, the depth of water tables and landscape position to supply water into the tilled zones, local climate and weather patterns, and a soil's texture and organic matter contents. However, the ability to predict precisely where and when FSS will occur is likely to be very difficult. The nature of how soil particles undergoing settling processes will in turn change the soil's pore characteristics (diameter, roughness, connectedness, and tortuosity) and have subsequent effects on soil water transport is immensely complex. Scientists' ability to predict such systems is difficult as these processes occur on a small

Figure 2

Hypothetical diagrams of (a) typical soil settling due to repeated wetting/drying and freezing/thawing cycles and (b) absence of significant soil settling during dry winter and spring months (fluffy soil syndrome [FSS]). Diagrams show relative soil porosity over time from harvest of the previous crop to the planting of the next crop. Tan shaded areas denote soil settling (a decrease in relative soil porosity) that occurs after primary tillage in the fall months.



scale that is obscured by the opaque nature of soil. Even if observations of these often hidden, small-scale processes were technologically possible, extensive real time, in situ monitoring would be needed to accurately characterize (or parameterize) the soil settling process and the subsequent effects on water transfer. However, some generalizations can be made based on what we do know about tillage practices and the mechanisms controlling soil deformation and water flows.

The USDA's National Agricultural Statistics Service reported 42, 39, and 31 million ha (105, 96, and 76 million ac) of US croplands with conventional tillage, no-till, and conservation tillage practices, respectively, during 2012 (USDA NASS 2014). Among these categories, most conventional and conservation tillage practices (essentially any tillage practice that aggressively tills or inverts throughout the top 10 to 30 cm [4 to 12 in] of soil) will potentially create the initial conditions necessary for FSS. Implements that provide tillage on the shallower end of this range (e.g., soils worked solely with a field cultivator) may not express FSS, even when post-tillage soil settling is minimal, if the underlying subsoil is adequately moist and not limited in supplying an upwards flux of water to the relatively thin tillage depth. The risk of FSS increases as the depth of tillage increases. This is due to the greater distances that water must flow from a moist subsoil to the seed/seedling. Other practices, such as strip tillage, which aggressively uses shanks or coulters to till in the plant row while leaving the interplant row mechanically untouched, are not likely candidates for FSS. This is because the interplant row stores significantly higher levels of soil water as compared to the tilled plant row (Alghamdi et al. 2016). The stored soil water in the adjacent interplant row may (1) supply adequate amounts of liquid water-film flow and water vapor flows to the seed/seedling and (2) supply enough moisture to the tilled zone to promote wetting/drying processes with subsequent soil settling.

For a tilled soil to obtain the necessary initial conditions for FSS and then for those properties to persist in time, the soil needs a minimum quantity of charged surface area. A soil innately low in the number of charged surfaces and low in physical quality (e.g., low organic matter sands) will immediately settle to a much greater extent than a soil innately high in the number of charge surfaces (e.g., high organic matter vertisols) (Horton et al. 2016). However, this is only true if we assume producers obtain seedbeds with small, crumb-sized soil aggregates void of large clods or smeared surfaces in soils with moderate-to-high levels of charged surfaces. An abundance of large clods may form if a soil with poor physical quality is tilled while too dry (Dexter and Birkas 2004; Dexter 2004). The same soil if tilled while too wet may cause smearing along the bottom of the plow depth or develop an abundance of smeared soil "slabs." Both situations would require additional tillage passes to break up clods and any smeared soil masses (Sitkei 1967; Ojeniyi and Dexter 1979).

SOIL MANAGEMENT CONSIDERATIONS AND TILLAGE ALTERNATIVES

Reduce Tillage. Tillage creates the initial conditions needed for FSS. Therefore, the best options for minimizing the risk of FSS is to limit tillage. Producers can reduce the depth of tillage, limit the total land area tilled, or transition away from tillage altogether. Shallow vertical tillage implements offer an efficient way to reduce the depth of tillage. These implements only scratch the soil surface while sizing crop residues into small pieces for quick breakdown while also thinning the crop residue layer for more efficient springtime soil warming and drying. If somewhat deeper tillage is still desired by the producer, then using a field cultivator prior to planting can accomplish a good compromise between chisel-plowing and vertical tillage. Strip tillage allows producers to till as deep as chisel plowing while minimizing the total land area tilled. This is done by tilling in rows where seeds will later be placed and leaving the interplant-row zones untouched. Although soil settling may still be minimal in the tilled rows, the moisture from the adjacent nontilled zones may provide an adequate supply of moisture for plant growth and for subsequent wetting/drying cycles that promote soil settling.

Minimize Field Traffic. Crop producers routinely arrange and then rearrange the soil's internal architecture during a crop year. For instance, soil compaction stems directly from the traffic of combines, weight wagons, grain carts, tractors, fertilizer carts and applicators, tillage implements, planters, and herbicide/pesticide carts and applicators. Tillage is then used to quickly alleviate the compaction with shanks, coulters, shovels, shares, and disc while also burying crop residues. At planting, the seed drill blades open the soil, and compaction wheels close the soil. A similar process occurs when injecting fertilizers. Overall, these field operations amount to a lot of soil disturbance. The more mechanical disturbance to the soil, the lower the soil aggregation and the more producers will desire tillage. By reducing field traffic, the desire for tillage as a means to alleviate compaction also decreases. A number of natural processes exist for rearranging the soil's internal architecture and alleviating soil compaction, processes such as freezing/thawing, wetting/drying, root penetration, burrowing animals, and decay of organic materials. Although these natural processes occur much more slowly than the process of tillage, changing management practices to minimize field traffic and rely on natural processes to alleviate soil compaction will help producers transition to using less tillage.

Develop and Maintain Stable Soil Aggregates. Stable aggregates are high in shear strength, abundant in internal particle-to-particle contact, efficient at protecting of soil organic carbon (C), and well-known for their ability to store significant quantities of water and nutrients near their center (Sexstone et al. 1985; Six et al. 1998; Bronick and Lal 2005). Therefore, a tilled soil that contains an abundance of stable soil aggregates will not be as likely to express FSS as compared to a tilled soil lacking stable aggregates. The soil aggregates will supply water and nutrients to the seed/seedling analogous to how the untilled portion of strip-tilled soil may provide water to the adjacent tilled zones. The only differences in these two situations are the scale at which the process works and the distance the water must travel from moist areas to the seed/seedling. However, if strongly aggregated soils are to be tilled, producers should target optimum soil moisture conditions so to avoid the formation of large clods (soil conditions too dry) and smearing (soil conditions too wet) of aggregates. Producers should seek out efficient practices to increase soil organic matter and therefore promote the formation of stable soil aggregates; such practices include incorporating high C manures, litters, green mulches, and crop rotations into their systems.

CONCLUSIONS

In recent years, relatively dry winter and spring months in the US upper Midwest and northern Great Plains regions have caused some tilled soils to undergo minimal settling. These soils have produced unique patterns of plant growth in the following growing season. When tilled soil does not settle over the winter and spring months, FSS occurs and results in crops suffering from inadequate soil particle-to-particle contact. Tillage initiates the conditions for soils to be at risk for FSS, but the absence of wetting/drying or freezing/thawing cycles is what allows the loosened soil state to persist into the following growing season with potentially detrimental effects on the crop and susceptibility for wind erosion. Producers can minimize their risk for FSS by reducing field-traffic derived soil compaction, reducing the depth and area of soil tillage, and by incorporating high C materials to promote the formation of stable soil aggregates.

REFERENCES

Alghamdi, R., A.L.M. Daigh, J. DeJong-Hughes, and A.F. Wick. 2016. Soil heating and drying among reduced tillage practices in frigid corn-soybean fields. Soil Management Impacts on Soil Properties and Soil C and N Dynamics: II. Soil and Water Management and Conservation Division. *In* Annual Meeting Abstracts. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Bouaziz, A., and L. Bruckler. 1989. Modeling of wheat imbibition and germination as influenced by soil physical properties. Soil Science Society of American Journal 53:219-227.

Bronick, C.J., and R. Lal. 2005. Soil structure and management: A review. Geoderma 124:3-22.

Carminati, A., A. Kaestner, P. Lehmann, and H. Fluhler. 2008. Unsaturated water flow across soil aggregate contacts. Advances in Water Resources 31:1221-1232.

Dagesse, D. 2016. Application of a thermodynamically based shrinkage equation to freezing induced bulk soil volume changes. Modeling Energy and Mass Transfer Processes at the Soil-Atmospheric Interface. Soil Physics and Hydrology Division. *In* Annual Meeting Abstracts. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Daigh, A.L., M.J. Helmers, E. Kladivko, Z. Zhou, R. Goeken, J. Cavadini, D. Barker, and J. Sawyer. 2014a. Soil water during the drought of 2012 as affected by rye cover crops in fields in Iowa and Indiana. Journal of Soil and Water Conservation 69(6):564-573, doi:10.2489/jswc.69.6.564.

Daigh, A.L., X. Zhou, M.J. Helmers, C.H. Pederson, R. Ewing, and R. Horton. 2014b. Subsurface drainage flow and soil water dynamic of reconstructed prairies and corn rotations for biofuel production. Vadose Zone Journal 13(4):177, doi:10.2136/vzj2013.10.0177.

Dexter, A.R. 2004. Soil physical quality: Part II. Friability, tillage, tilth and hard-setting. Geoderma 120:215-225.

Dexter, A.R., and M. Birkas. 2004. Prediction of the soil structures produced by tillage. Soil and Tillage Research 79:233-238.

Edwards, A.C., R. Scalenghe, and M. Freppaz. 2007. Changes in the seasonal snow cover of alpine regions and its effect on soil processes: A review. Quaternary International 162-163:172-181.

Grifoll, J., J.M. Gasto, and Y. Cohen. 2005. Non-isothermal soil water transport and evaporation. Advances in Water Resources 28:1254-1266.

Hamilton, A.B. 1966. Freezing shrinkage in compacted clays. Canadian Geotechnical Journal 3:1-17.

Horton, R., R. Horn, J. Bachmann, and S. Peth. 2016. Hartge/Horn: Essential soil physics. An introduction to soil processes, functions, structure and mechanics. 1st English edition, based on the 4th German edition. Stuttgart, Germany: E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. obermiller).

Jordan, W.R. 1983. Whole plant response to water deficits: An overview, ed. H.M. Taylor, W.R. Jordan, and T.R. Sinclair. *In* Limitations to Efficient Water Use in Crop Production. Madison, WI: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Nassar, I.N., and R. Horton. 1997. Heat, water, and solution transfer in unsaturated porous media: I – Theory development and transport coefficient evaluation. Transport in Porous Media 27:17-38.

Ojeniyi, S.O., and A.R. Dexter. 1979. Soil factors affecting the macro-structures produced by tillage. Transactions of the American Society of Agricultural Engineering 22:339-343.

Parlange, M.B., A.T. Cahill, D.R. Nielsen, J.W. Hopmans, and O. Wendroth. 1998. Review of heat and water movement in field soils. Soil and Tillage Research 47:5-10.

Schott, L.R., A. Lagzdins, A.L.M. Daigh, K. Craft, C. Pederson, G. Brenneman, and M.J. Helmers. 2017. Drainage water management effects over five years on water tables, drainage, and yields in southeast Iowa. Journal of Soil and Water Conservation. *In Press.*

Sexstone, A.J., N.P Revsbech, T.B. Parkin, and J.M. Tiedje. 1985. Direct measurements of oxygen profiles and denitrification rates in soil aggregates. Soil Science Society of America Journal 49:645-651.

Sitkei, Gy. 1967. A Mezőgazdasági Gépek Talajmechanikai Problémái (Soil Mechanical Problems of Agricultural Tools). Budapest: Akadémiai Kiadó.

Six, J., E.T. Elliott, K. Paustian, and J.W. Doran. 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Science Society of America Journal 62:1367-1377.

Triplett, G.B., Jr., and W.A. Dick. 2008. No-tillage crop production: A revolution in agriculture! Agronomy Journal 100:S153-S165.

USDA NASS (National Agricultural Statistics Service). 2014. 2012 Census of Agriculture: United States Summary and State Data. AC-12-A-51. Washington, DC: USDA National Agricultural Statistics Service.

Wang, E., R.M. Cruse, X. Chen, and A. Daigh. 2012. Effects of moisture condition and freeze/thaw cycles on surface soil aggregate size distribution and stability. Canadian Journal of Soil Science 92:529-536.

Wuest, S.B. 2002. Water transfer from soil to seed: The role of vapor transport. Soil Science Socieity of America Journal 66:1760-1763.

Wuest, S. 2007. Vapour is the principal source of water imbibed by seeds in unsaturated soils. Soil Science Research 17:3-9.