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Messages

Pray, listen, and share ideas with others to enhance your soil physics research

Robert HORTON

Soil science, including soil physics, is a relatively young discipline that seeks to deepen the fundamental understanding of soil properties and processes and to develop practical management skills required to use soils sustainably. Most research efforts in the twentieth century centered on agricultural soils. Late in the twentieth century, the focus of soil science began to shift from maximizing production (food, feed, and fiber) to sustainable production that sought to balance productivity with environmental stewardship of the soil resource. It is clear that soils serve not only agricultural uses but much more. As awareness increases on the importance of soils, the responsibility to care for soils as good stewards also increases. Because soils are a prominent natural resource connected to food (world hunger), water (quality and quantity), climate (surface energy balance and climate change), bioenergy, and transportation (road foundation), the opportunities and necessity for soil physics research will increase. My thoughts about soils as a vital natural resource are found at the following link — https://youtu.be/CDJE45YPMu8.

Seeking a career in science research is a risky choice, because research involves pushing the knowledge envelope into the unknown with no guarantees for success. To reduce risk and overcome anxiety, it is important to have multiple sources of motivation and inspiration to support a research career. Common sources of motivation and inspiration are direct observations of the natural world, teachers and mentors, favorite journal authors, and attending conferences. These have all helped me in my career. I also benefitted from two additional sources that receive less attention in our science community — prayer, and having a trusted group of colleagues that use 'brain-storming' discussions (thinking and planning activities) to develop new ideas. I will first focus my comments on how faith in God and praying helped me as a scientist, and then I will provide two examples on how discussions and collaborations with others helped to enhance my soil physics research contributions.

Importance of Faith and Prayer

Historically, early 'thinkers' or intellectuals who established our science disciplines were mostly people of faith. The integration of their faith with reason led them to explore the beauty and wonder of creation in order to better know and serve God and to better serve humanity. Blaise Pascal, whom the S.I. units of pressure, pascals (Pa), are named after, was a dedicated scientist and person of faith. Pascal argued that a wise person should seek to believe in God. If God does not exist, such a person will have only a finite loss (time or money), whereas if God does exist, they can receive infinite gains (eternity in Heaven) and avoid infinite losses (eternity in Hell). Pascal demonstrated that faith and reason complement one another, because it is reasonable to have faith, but the faith must be reasonable.

Many scientists, whether they are persons of faith or not, do not regularly pray for inspiration. I was such a person early in my career. I did not see the consistency of faith and reason. I went to church to pray, while at work I used my intellectual faculties. Aspects of my life were fragmented, with my work, family life, and spiritual life being somewhat independent of each other. Work garnered most of my attention. Things changed early in my academic career, when tragedy hit my family and deeply affected my life. My 1-year old daughter died in an accident. This shook me to the core. In my grief I turned to God, and over a period of time I began to experience the presence of God close to me. With a growing relationship with God, I decided to strive for a healthy work-life balance by prioritizing faith, family, and work

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Agronomy Department, Iowa State University, Ames, Iowa 50011 USA.

(see https://doi.org/10.2134/csa2016-61-7-12). I continued to work hard, but I did not spend all of my waking time at work.

Instead of partitioning my faith and science activities, I integrated them, striving to be the same whole person at home, at church, and at work. Having God central to my life inspires, informs, and enriches all the aspects and relationships in my life. It produces wonders for my work motivation by amplifying my desire to honor God and serve him by caring for creation and caring for humanity. I regularly pray for guidance and inspiration in my research and in my interactions with others. For example, to help develop the next generation of scientists, I flipped my mentoring style to serve my students rather than asking my students to serve me (see https://doi.org/10.1002/csan.20525).

I often begin my work day with a prayer composed by St. Thomas Aquinas, *"Creator of all, source of all light and wisdom, you made everything. Let a ray of your light penetrate the darkness of my mind. Take from me all darkness of sin or ignorance. Give me a keen understanding, a good memory, and the ability to grasp things correctly and completely. Help me to be exact in my explanations and to express myself thoroughly and clearly. Show me how to begin my work, direct my progress, and help me complete it. I ask this through Christ our Lord. Amen."*

Listening to and Sharing Ideas with Others

Another great source of motivation and inspiration for me has been group discussion. Whether planning, designing, reviewing data, analyzing, interpreting, sharing ideas, thinking out loud, asking questions, pondering, or seeking guidance — group discussions are helpful. Ideas emerge from group discussions or 'brain storming' sessions. There is a table outside of my Iowa State University office where many group discussions have occurred. We just refer to it as 'the table,' as in let's meet at 'the table.' I have fond memories of many great discussions held at 'the table,' because many of the shared ideas enhanced my research collaborations. Everyone (faculty colleague and student alike) was free to express their thoughts, ideas, concerns, and encouragements at 'the table.' Early career scientists, especially graduate students and post-docs, taught me several things at these discussions. There are many success stories that resulted from fruitful discussions at 'the table,' but I will limit myself to only share two stories — the automated tension infiltrometer and the thermo-TDR sensor. These are two examples depicting how good fruit can emerge from listening to and sharing ideas with others.

Throughout my career, I have worked on various aspects of soil hydrology. Soil water infiltration, soil water storage, soil water drainage, plant water relationships, and soil water evaporation. My research focus area is coupled heat, water, and chemical transfer in soils. I collaborated on a device, automated tension infiltrometer, to measure saturated and unsaturated hydraulic conductivity in field soils. It also determines soil pore size distribution and solute transport properties. Because we did not have ways to measure energy and mass fluxes in soil, I collaborated with others to develop ways to quantify soil heat and mass fluxes. A heat pulse sensor (reported by Gaylon Campbell, Keith Bristow, and Gerard Kluitenberg) was combined with a TDR sensor (reported by Clarke Topp) to produce a thermo-TDR sensor. Analyzing thermo-TDR measurements has enabled in situ determinations of sensible heart flux, soil liquid water flux, vapor flux (evaporation), and transient ice formation and ice melting. These measurements are possible in rigid soils, and also in non-rigid soils that experience dynamic porosity and bulk density. I think these instruments will assist future investigations of coupled heat and water processes at the land surface and in the subsurface. They will contribute to future energy balance and water balance discoveries.

The story behind developing the automated tension infiltrometer

In 1987 I was working at Iowa State University when a stranger knocked on my office door. He introduced himself as Mark Ankeny, a crop science graduate student. He told me that he was interested in plant roots, and he asked me if I had any ideas on how to make measurements that would enable him to estimate how plant roots would distribute and grow in a particular soil. I told him that I did not know with certainty which soil measurements would provide the best estimators for root development and growth. We discussed a series of measurements including cone penetration resistance, pore size distribution derived from water retention curves, air permeability, and saturated and unsaturated hydraulic conductivity. I recommended that he explore fluid flow measurements because fluid flow occurred in connected soil pores which might relate well to how roots grow in connected pores. I had a homemade tension (disc) infiltrometer in my laboratory, and since I was not using it at the time, I loaned it to Mark and asked him to make some saturated and unsaturated water flow measurements on soils to see if he could correlate them to root growth. He thanked me and left my office. When he left, I was not sure if I would ever see him or the tension infiltrometer again.

Several months later, Mark returned to my office. He said that he had an idea on how to improve the design of the tension infiltrometer that I had loaned him. I listened to him as he described how adding pressure transducers to the infiltrometer would enable automating the measurements. By connecting the transducers to a datalogger, saturated and unsaturated infiltration rates versus time could be measured directly. In Mark's opinion, the infiltration data quality would be greatly improved with the new design. After he explained his idea to me, I completely agreed with him. We hired a local machine shop to build several newly designed automated tension infiltrometers. Ankeny et al. (1988) described the automated tension infiltrometer design, which provided a large improvement in the quality of infiltration with time measurements. Ankeny et al. (1990) reported the effects of tillage and agricultural equipment traffic on unsaturated infiltration rates measured with the automated tension infiltrometer.

At first, the automated tension infiltrometer simply improved the quality of infiltration measurements, and it was used to quantify the effects of tillage and traffic on soil water infiltration. However, it did not yet provide any new information on saturated and unsaturated hydraulic conductivity, nor did it address the original question on how to use soil measurements to estimate potential root growth. I discussed these points with Mark, and I told him that I thought the high quality infiltration measurements could be used to quantify 'pore size distribution' and also to determine saturated and unsaturated hydraulic conductivity. Mark felt quite challenged by my comments, in part because he did not have a strong background in soil physics or in mathematical analysis. Never-the-less he took my comments to heart and began to think seriously about how to further interpret the tension infiltrometer measured infiltration with time curves. He had an idea that measuring steady state infiltration fluxes at a series of tensions could produce the saturated and unsaturated hydraulic conductivity values for a particular field. He came to my office and sketched out his idea on a piece of paper. Although his drawing was cartoon-like, I could follow his thought process, and I was convinced that his idea had merit. I developed the mathematical steps that matched his conceptual idea, and we had a new method to determine saturated and unsaturated hydraulic conductivity from tension infiltration measurements (Ankeny et al., 1991). The automated tension infiltrometer method became one of the most widely applied ways to determine field hydraulic conductivity values. Later, a post-doc named Binayak Mohanty used tension infiltrometer measurements (Mohanty et al., 1996) to estimate soil pore size distributions, which brought us back full-circle to the original question Mark had asked on how to characterize soil pores for plant root growth.

Jaynes et al. (1995) reported that a tension infiltrometer could be used to determine solute transport properties of the mobile-immobile model. They applied a suite of tracers to soil via a tension infiltrometer. Casey et al. (1998) measured hydraulic conductivity and solute transport properties of field soil. More recently, I hosted a Japanese scientist, Junko Nishiwaki, who used tension infiltrometer measurements to characterize time changes in soil hydraulic conductivity following tillage (Nishiwaki and Horton, 2020). Junko's work clearly shows that soil bulk density increases with time following tillage, and soil hydraulic properties change as bulk density changes. I think that the impact of soil bulk density temporal changes on soil hydraulic and thermal properties will be increasingly studied in the future. We must reject the assumption that soil physical properties are constant in time. Developing a sensor that measures transient, in situ bulk density values will provide new opportunities for comprehensive studies of coupled heat and mass transfer in non-rigid soils. The thermo-TDR sensor is such a sensor.

The story behind developing the thermo-TDR sensor

In 1997 I was working in my office when a man, Tusheng Ren, knocked on my office door. I welcomed him into my office. He told me that he had recently completed his PhD program in Canada, and that he moved to Iowa to be with his wife while she completed her graduate studies at Iowa State University. He said that he wanted to work with me and asked if I could hire him as a post-doc. I told him that I had recently hired a post-doc, Kosuke Noborio, and that I did not have funding for another post-doc position. Dr. Ren then asked me if he could work with me for free — no salary. I did not want to take advantage of Dr. Ren, so rather than have him work for free, we agreed to first meet and discuss possible research ideas. Meanwhile, I would acquire some funds to hire him, in case we decided on a suitable collaborative research study. The research idea that emerged from our discussions was to try to improve a sensor that was first described by Noborio et al. (1996). The sensor, which we later named the thermo-TDR sensor, was a combination of a heat pulse sensor and a TDR sensor. It was able to measure soil thermal properties and soil electrical properties at the same scale. The improved sensor design was reported by Ren et al. (1999), Ren et al. (2003), and Peng et al. (2019).

Initially, sensor measurements were used to characterize soil thermal properties, water content, and bulk electrical conductivity, but we hoped that additional soil properties could be derived from these measurements. Dr. Ren, Dr. Noborio and I had many discussions at 'the table.' We held several 'brainstorming' sessions, where we allowed our imaginations to explore potential uses of the new sensor. We discussed possible experiments to learn new things about transient soil properties and processes. Many of the ideas we considered at 'the table' discussions were actually studied over the next two decades by a host of our subsequent graduate students and colleagues.

Ochsner et al. (2001) described how thermo-TDR measurements could be used to simultaneously determine soil water content and soil bulk density. Soil water content was determined from the TDR measurement of apparent dielectric constant, and bulk density was determined from the heat pulse measurement of volumetric heat capacity, which was a function of water content and bulk density. Measuring thermal and electrical properties together enabled the determination of water content and bulk density. Liu et al. (2013) described a way to self-calibrate sensors in situ. Liu et al. (2014) used the method to measure in situ transient water content and bulk density. The ability to measure transient water content and bulk density opened the possibility to determine their effects on other soil physical properties, such as water retention, hydraulic conductivity, and thermal properties. Initial studies were described by Zhang et al. (2018) on water retention, Kool et al. (2019) on hydraulic conductivity, and Tong et al. (2020) on thermal properties. Much future work is needed on related topics.

Have you noticed how few methods exist to measure heat and mass fluxes in soil? I am not aware of many practical methods to determine fluxes in soil. It is somewhat surprising that soil physicists have not developed methods to directly measure soil water fluxes. Most water flux estimates require a known value of hydraulic conductivity. Because hydraulic conductivity varies several orders of magnitude over the normal range of ambient soil water contents, estimates of hydraulic conductivity are crude and noisy, and thus soil water flux estimates are rough and more qualitative than quantitative. Developing a reliable method to quantify soil water flux without the need for hydraulic conductivity would represent a much needed breakthrough for soil physics. In a progressive step by step manner, the thermo-TDR sensor has been shown to be able to measure soil heat flux, liquid water flux, vapor flux (evaporation), and latent heat flux for freezing and thawing ice contents. The flux measurement approaches are new and should be greatly explored and applied in future heat and mass transfer investigations. Here, I will briefly describe how to determine fluxes in soil.

Heat flux plates are commonly used to measure soil heat fluxes. However, heat flux plates do not measure surface heat fluxes, because they must be buried in the soil. They cause problems by blocking liquid water movement and water vapor movement, thus distorting the soil water distribution near the plates. Because water content effects soil thermal properties, distortions in water content cause distortions in the temperature and heat flux distributions. Ochsner et al. (2006) and Peng et al. (2017) reported that heat pulse measurements of soil thermal conductivity used in combination with ambient temperature gradients could accurately measure soil heat flux. The heat pulse sensors can be buried at shallow depths very near to the soil surface, because they provide minimal interference to liquid and vapor water movement. Thus the heat pulse sensor has advantages over heat flux plates by measuring heat flux very near to the soil surface, which is important for surface energy balance studies. Additional future studies and applications of these measurements are warranted.

The soil physics community is in need of sensors to measure soil liquid water flux. Wang et al. (2002) showed how heat pulse sensor measurements could be used to determine soil water infiltration flux. Their mathematical analysis showed that heat transfer could be used as a proxy for water flux. A three-needle heat pulse sensor was placed in soil with an upper needle positioned upstream from the center heater needle and a lower needle positioned downstream from the center heater needle. Once a pulse of heat was applied to the center needle, heat transferred toward the upstream needle by conduction alone, while conduction and convection carried heat towards the downstream needle. Thus, temperature increases at the downstream needle were larger than those at the upstream needle. The logarithm of the ratio of downstream temperature to upstream temperature was reported to be proportional to the soil water flux density. At last, we had a method to determine soil water flux. Gao et al. (2006) verified the Wang et al. (2002) method under controlled laboratory conditions. Tian et al. (2018) presented a thermo-TDR based method to determine upward liquid fluxes in response to soil water evaporation. They verified the new method by combining their field measured soil water fluxes with water potential measurements to determine unsaturated hydraulic conductivity values, which were similar to independently measured laboratory values. Both of these soil water flux methods are available for further verification and application under field conditions.

For quite some time it has been possible to estimate soil water evaporation rates from wet soil surfaces (Stage 1 conditions). However, it is much more challenging to estimate soil water evaporation rates from drying soil surfaces (Stage 2 and 3 conditions). Heitman et al. (2008) presented a sensible heat balance method based on heat pulse sensor measurements to estimate Stage 2 and 3 soil water evaporation rates. The Heitman et al. (2008) method determined evaporation as a function of depth and time. Thus, they provided a way to determine water vapor fluxes in soil. Wang et al. (2017) verified the sensible heat balance method by comparing heat pulse sensor determined daily evaporation values with field weighing lysimeter soil water evaporation values. The daily evaporation values from both methods matched well. This soil water vapor flux method is available for further applications under field conditions.

The liquid water flux and water vapor flux methods perform well in unfrozen soil conditions. However, some soils undergo periods of freezing and thawing. Therefore, it is important to develop a method to determine soil ice contents during times of freezing and thawing. Kojima et al. (2013) performed a numerical study to evaluate the potential of a sensible heat balance method to estimate soil ice contents during freezing and thawing conditions. Based on the numerical investigations, the sensible heat balance method performed well. Kojima et al. (2016) tested the sensible heat balance method to determine soil ice contents in a laboratory study. They used heat pulse sensor measurements to make the sensible heat balance calculations. Because heat of fusion was smaller than heat of vaporization, soil ice content was more difficult to determine than soil water evaporation, and the sensible heat balance method was limited to temperatures between -5 and 0 °C. At colder temperature values, changes in volumetric heat capacity were used to estimate changes in soil ice content. Tian et al. (2020) provided additional insights on using thermo-TDR sensors to determine soil ice contents. Additional work is needed to further verify and develop methods to determine transient soil ice contents.

In closing, I hope that you, my soil physics colleagues, realize that we have much more soil physics to learn (properties, processes, and applications) in the future than what we currently know. The expanding range of interest in and opportunities for soils makes this an exciting time period for soil science in general and soil physics in particular. I have described two examples, tension infiltrometer and thermo-TDR sensor, of how I got started and followed through on unexpected, yet very fruitful, research topics. Notice that in both examples my involvement began via discussions with young scientists. Initial research ideas emerged from our discussions. After making some early advancements, additional discussions led to new ideas for applications that we did not anticipate at the beginning. So, if you listen to others and discuss possibilities, research ideas will emerge. Also, notice that there is much more research that can be done with tension infiltrometers and thermo-TDR sensors. They are instruments that enable measurements of soil properties and fluxes, but it will take your imagination to involve them in research studies to further explore coupled heat and mass transfer in soil.

In summary, for motivation and inspiration, I recommend that you pray, observe, listen, think, and engage in group discussions.

Fig. 1 Group discussions at 'the table' (Iowa State University, left photo) and at Meiji University (right photo).

References

Ankeny, M.D., Ahmed, M., Kaspar, T.C. and Horton, R. (1991): A simple field method for determining unsaturated hydraulic conductivity. Soil Sci. Soc. Am. J., 55: 467–470.

Ankeny, M.D., Kaspar, T.C. and Horton, R. (1988): Design for an automated tension infiltrometer. Soil Sci. Soc. Am. J., 52: 893–896.

Ankeny, M.D., Kaspar, T.C. and Horton, R. (1990): Characterization of tillage effects on unconfined infiltration measurements. Soil Sci. Soc. Am. J., 54: 837–840.

Casey, F.X., Logsdon, S.L., Horton, R. and Jaynes, D.B. (1998): Measurement of field soil hydraulic and solute transport parameters as a function of water pressure head. Soil Sci. Soc. Am. J., 62: 1172–1178.

Gao, J., Ren, T. and Gong, Y. (2006): Correcting wall flow effect improves the heat-pulse technique for determining water flux in saturated soils. Soil Sci. Soc. Am. J., 70: 711–717.

Heitman, J.L., Xiao, X., Horton, R. and Sauer, T.J. (2008): Sensible heat measurements indicating depth and magnitude of subsurface soil water evaporation. Water Resour. Res., 44: W00D05, doi:10.1029/2008WR006961.

Jaynes, D.B., Logsdon, S.D. and Horton, R. (1995): Field method for measuring mobile/immobile water content and solute transfer rate coefficient. Soil Sci. Soc. Am. J., 59: 352–356.

Kojima, Y., Heitman, J.L., Flerchinger, G.N. and Horton, R. (2013): Numerical evaluation of a sensible heat balance method to determine rates of soil freezing and thawing. Vadose Zone J., 12: vzj2012.0053.

Kojima,Y., Heitman, J.L., Flerchinger, G.N., Ren, T. and Horton, R. (2016): Sensible heat balance estimates of transient soil ice contents. Vadose Zone J., 15: vzj2015.10.0134.

Kool, D., Tong, B., Tian, Z., Heitman, J.L., Sauer, T.J. and Horton, R. (2019): Soil water retention and hydraulic conductivity dynamics following tillage. Soil Till. Res., 193:95-100, doi:10.1016/j.still.2019.05.020.

Liu, G., Wen, M., Chang, X., Ren, T. and Horton, R. (2013): A self-calibrated dual probe heat pulse sensor for in situ calibrating the probe spacing. Soil Sci. Soc. Am. J., 77: 417–421.

Liu, X. Lu, S., Horton, R. and Ren, T. (2014): In situ monitoring of soil bulk density with a thermo-TDR sensor. Soil Sci. Soc. Am. J., 78:400-407.

Mohanty, B.P., Horton, R. and Ankeny, M.D. (1996): Infiltration and macroporosity under a row crop agricultural field in a glacial till field. Soil Sci., 161: 205–213.

Nishiwaki, J. and Horton, R. (2020): Temporal changes in soil hydraulic conductivity in saturated and unsaturated fields. Paddy Water Environ., 18: 677–686, doi:10.1007/s10333-020-00810-x.

Noborio, K., McInnes, K.J. and Heilman, J.L. (1996): Measurements of soil water content, heat capacity, and thermal conductivity with a single TDR probe. Soil Sci., 161: 22–28.

Ochsner, T.E., Horton, R. and Ren, T. (2001): Simultaneous water content, air-filled porosity, and bulk density measurements with thermal-time domain reflectometry. Soil Sci. Soc. Am. J., 65: 1618–1622.

Ochsner, T.E., Sauer, T.J. and Horton, R. (2006): Field tests of the soil heat flux plate method and some alternatives. Agron. J., 98: 1005–1014.

Peng, W., Lu, Y., Xie, X., Ren, T. and Horton, R. (2019): An improved thermo-TDR technique for monitoring soil thermal properties, water content, bulk density, and porosity. Vadose Zone J., 18: 190026, doi:10.2136/vzj2019.03.0026.

Peng, X., Wang, Y., Heitman, J., Ochsner, T., Horton, R. and Ren, T. (2017): Measurement of soil-surface heat flux with a multi-needle heat-pulse probe. Eur. J. Soil Sci., 68: 336–344, doi:10.1111/ejss.12421.

Ren, T., Noborio, K. and Horton, R. (1999): Measuring soil water content, electrical conductivity, and thermal properties with a thermo-TDR probe. Soil Sci. Soc. Am. J., 63: 450–457.

Ren, T., Ochsner, T.E. and Horton, R. (2003): Development of thermo-time domain reflectometry for vadose zone measurements. Vadose Zone J., 2: 544–551.

Tian, Z., Kool, D., Ren, T., Horton, R. and Heitman, J.L. (2018): Determining in-situ unsaturated soil hydraulic conductivity at a fine depth scale with heat pulse and water potential sensors. J. Hydrol., 564: 802–810, doi:10.1016/j.jhydrol.2018.07.052.

Tian, Z., Kojima, Y., Heitman, J.L., Horton, R. and Ren, T. (2020): Advances in thermo-time domain reflectometry technique: Measuring ice content in partially frozen soils. Soil Sci. Soc. Am. J., 84: 1519–1526, doi:10.1002/saj2.20160.

Tong, B., Kool, D., Heitman, J.L., Sauer, T.J., Gao, Z. and Horton, R. (2020): Thermal property values of a central Iowa soil as functions of soil water content and bulk density or of soil air content. Eur. J. Soil Sci., 71: 169–178, doi:10.1111/ejss.12856.

Wang, Q., Ochsner, T.E. and Horton, R. (2002): Mathematical analysis of heat pulse signals for soil water flux determination. Water Resour. Res., 38: 10.1029/2001WR1089.

Wang, Y., Ochsner, T., Heitman, J., Horton, R., Xue, X. and Ren, T. (2017): Weighing lysimeter data confirm the accuracy and precision of the heat-pulse technique for measuring daily soil evaporation. Soil Sci. Soc. Am. J., 81: 1074–1078, doi:10.2136/sssaj2017.02.0049n.

Zhang, M., Lu, Y., Heitman, J., Horton, R. and Ren, T. (2018): Temporal changes of soil water retention behavior as affected by wetting and drying following tillage. Soil Sci. Soc. Am. J., 81: 1288–1295, doi:10.2136/sssaj2017.01.0038.