Basic Information

Project No.: W4188
Title: Soil, Water, and Environmental Physics to Sustain Agriculture and Natural Resources
Period Covered: 10/01/2020 to 09/30/2021
Date of Report: 03/31/2022

W4188 2022 Meeting Minutes

Format: Virtual Meeting via Zoom platform
Dates: January 3-4, 2022 from 11 AM to 5:15 PM EST
Group annual reports are due on Monday, January 31st, 2022
Minutes taken by Andres Patrignani, Kansas State University

Former Chair: Ryan Stewart
Current Chair: Fred Zhang
Secretary: Andres Patrignani
Treasurer: Robert Heinse

The meeting was held in virtual format using the Zoom platform due to increasing concerns about the COVID-19 Omicron variant that started to rapidly spread across the United States in December 2021.

Participants: Scott Jones, Fred Zhang, Andres Patrignani, David Robinson, Steve Evett, Ole Wendroth, Asmeret Asefaw, Wei Zhang, Robert Heinse, Manoj Shukla, Markus Tuller, Yan Jin, Robert Horton, Dani Or, Thomas Harter, Tamir Kamai, Briana Wyatt, Hoori Ajami, Todd Skaggs, Salini Sasidharan, Fatema Kaniz (graduate student), John Nieber, Ryan Stewart, Jingyi Huang, Rose Shillito, Atac Tuli, Carlos Ochoa, Daniel Ullom, Hui Yang (postdoc), Igor Assis, Laosheng Wu, Joan Wu, Morteza Sadeghi, Michael Young, Amninder Singh, Shane Franklin, Majdi ABou, Najm, Iael Raij-Hoffman, Teamrat Ghezzehei, Isaya Kisekka, Elia Scudiero, J Chen, Amir Haghverdi, Markus Flury, Thomas Harter, Hanni Haynes, Rober Ewing, Thijs Kelleners, Kenneth Carroll, Tim Green, Amir Haghverdi, Tyson Ochsner, Jirka Simunek, Yingxue Yu (graduate student), Scott Bradford, Nuwan Wijewardane, Hendriywinanto, Amminder Singh, Spencer Patrick, Hanni Haynes (graduate student), Joan Wu, Tiantian Zhou, Thomas Harter, Theodor Bughici, Yusen Yuan, Zampela Pittaki, Shane Franklin, Paulo Ivonir Gubiani (postdoc), Mahyar Naseri, Joan Wu, Jie Hu, Jeremy Giovando, Chihiro Naruke, Daniel Ullom, Will Nichols, Hassan Dashtian, Jan Hopmans, Markus Berli, Jack Brookshire, Spencer Patrick, Saul Sorek

Maximum online attendance reached a total of 62 participants, and attendance was mostly greater than 55 participants through the entire meeting.

Business meeting

Selection of new Treasurer

Robert Heinse volunteered to serve as the project Treasurer one more year. The group approved this arrangement. Robert has been serving as Treasurer since he chaired the group.

Selection of new secretary

Tyson nominated **Briana Wyatt**. Wei Zhang, second. Briana agreed to serve in this capacity and was unanimously approved by the meeting attendees.

Discussion with Administrative Advisor (Walter Bowen)

The project account currently has a total of $14,000 that need to be spent by September 30, 2022.
Ryan Stewart proposed to sponsor students to travel and work in other labs and/or a retreat for the team writing the new project proposal.
Michael Young proposed to concentrate the transfer one time
Ole Wendroth asked whether we can request a no-cost extension
Walter Bowen suggested to **spend at least 50% of remaining funds, so that we can carry over the money without additional paperwork**.
Scott Jones reported that there appear to be some inconsistencies in terminology between AES and W4188 reporting platforms.
Walter Bowen mentioned that NIFA is working on a new report platform that will be ready in early February 2022 and **official project reports are due on April 1, 2022**.

Ideas to spend remaining funds:

- Graduate student travel award to SSSA annual meeting in 2022
- Graduate student travel for the W4188 annual meeting in 2023
- Graduate student research award to travel and work in other labs
- Send an early career member to go to the Kirkham 2022

Michael Young suggested centralizing project money to minimize paperwork and limit the number of transfers.
Michael Young highlighted the importance of collaboration. Purchase of instrument for research should be in partnership with other project members.

Robert Heinse mentioned that the current project account balance is about $3,000 to 4,000.

Jan Yin brought up some concerns about how different universities allocate annual funds.

Walter Bowen mentioned that funding ranges from $0 to about $14,000 per year depending on the institution. Several members stated that funds from this project represent part of their salary. Some universities may not pass any resources to the PI since salary is already part of the

contribution, while other institutions use funds for annual allocations and even to create internal competitive grants to upgrade equipment and purchase instrumentation (e.g., University of Hawaii, Kansas State University).

Plan for annual meeting in 2023
Ole Wendroth: Early January is fine. Extend the meeting one more day (total of 3 days).
Wei Zhang and Majdi Abou Najm also suggested the first week of January
Steve Evett and John Nieber suggested the inclusion of a virtual aspect to increase attendance.
Robert Heinse proposed to have a separate virtual business meeting to leave more time for presentations and discussion.
Ryan Stewart reminded CES show is January 5-8
Thomas Harter proposed to spend the afternoon on Monday, January 2nd for planning and writing.

Monday, January 3, 2022

Asmeret Berhe, Professor of soil biogeochemistry University of California, Merced. Persistence of soil organic carbon to environmental forcings like droughts and wildfires. Described traditional and new paradigms in SOM dynamics. How fast do we expect SOM to change with a changing climate? How does desiccation affects SOM? We should look at soil organic carbon dynamics considering the entire soil profile, not just the top soil. Fate of pyrogenic carbon (product of incomplete combustion) after fires is mostly dictated by the interaction with the hydrological cycle rather than microbial decomposition.

Asmeret also provided insights about equity, diversity and inclusion in soil sciences.
Soil science within the U.S. is much less diverse than larger U.S. population, and is also one of the least diverse disciplines within STEM education. The younger generation of soil scientists is more diverse than the senior generation of soil scientists. Nearly 75% of PhD students in soil sciences report experiencing gender harassment or racial discrimination (mostly common by supervisors). Academia is only second to the military in harassment.

Chaudhary, V.B. and Berhe, A.A., 2020. Ten simple rules for building an antiracist lab. PLoS computational biology, 16(10), p.e1008210. https://doi.org/10.1371/journal.pcbi.1008210

Panel #1

- **Markus Flury and Joan Wu**. Washington State University. Plastics in biosolids amended soils. Possible plastic uptake by plant roots and earth worms. Encouragement to promote research in Vadose Zone Journal.

- **Yan Jin.** University of Delaware. Impacts of sea-level rise and coastal flooding on the physical chemical, biological, and engineering properties of coastal soils. Macropore

effects on salt accumulation and distribution. Rhizosphere biophysical processes. Plant-growth-promoting rhizobacteria in soil properties and water. Preferential flow and biogeochemical processes. Unexplored role of preferential flow in soil carbon dynamics (https://doi.org/10.1016/j.soilbio.2021.108398).

- **Robert Heinse**. Idaho State University. Assessment of soil water stress in microgravity environments for the advance of plant habitats on the international space station. Optimizing water use for small plot organic vegetable and fruit production in the Palouse region.

- **Wei Zhang**. Michigan State University. Emerging trend in embracing One Health (health of people, health of animal, and health of the environment). Plant uptake of pharmaceutical from soils. PFAS exposure via food crops in addition to drinking water.

- **Briana Wyatt**. Texas A&M. Validation of a lithium foil cosmic-ray neutron detector. Soil characterization of stations of the Texas Mesonet. Impact of land cover changes on ground water recharge. Improving streamflow forecasting using remote sensing data.

- **Ryan Stewart**. Virginia Tech. Carbon dioxide soil profiles in normal soils and soils over karst features. Developing a passive flow-weighted water sampler for measuring plot runoff. Quantify soil potassium and water availability in vineyards.

- **Discussion**: Upscale preferential flow. Hotspots may remain dormant because much of the time macropores remain empty. Only when there is ponding these larger pores will become active and microbial activity will take place. Emphasis on preferential flow of water and the fate of pharmaceuticals and soil respiration. Discussion on upscaling pore and aggregate processes to the field and catchment scales. What is the measurement scale of soil carbon dynamics? How do we relate micro and macroscale soil processes? How do we transfer information across scales? How do we build quantifiable macropore networks for detailed study and modeling of preferential flow?

<u>Panel #2</u>

- **Hoori Ajami**. University of California Riverside. Understanding groundwater response to meteolrological droughts using data driven and integrated modeling approaches. How long does it take for meteorological droughts (lack of precipitation) to propagate into groundwater? On average to recover 3 years, but for intense droughts it can take up to 10 years. Characaterize mountain aquifer recharge Early career).

- **John Nieber**. University of Minnesota. Hydrological regionalization for streamflow prediction. Extrapolate what is happening in one watershed to another. Characterization of Connect multiple catchments collectively. CAMELS dataset watersheds. Use of random vectors as surrogate to physical watershed descriptors.

- **Thomas Harter**. University of California-Davis. Groundwater-Food Nexus. Basin scale ground water sustainability in irrigated agriculture. Non-point source pollution.

- **Jingyi Huang**. University of Wisconsin-Madison. High resolution soil moisture mapping and drought forecasting using remote sensing and machine learning. Spectral technologies for estimating soil hydraulic properties.

- **Carlos Ochoa**. Oregon State University. Surface water and groundwater interactions. Water recharge and interception in juniper-encroached landscapes. Sites in Oregon and Mexico.

- **Amir Haghverdi.** University of California-Riverside. Delineation of field management zones using remote sensing NDVI. Diving fields anywhere between 1 and 3 zones seems to reduce the intra-zone spatial variability. Possible consideration of transient management zones rather than fixed zones.

- **Discussion**: Temporal scale of groundwater recharge. Redistribution of deep water to shallow water. Need for deep sensors. Go back to neutron probe measurements. Use of stable isotopes to partition plant water uptake.

Tuesday, January 4, 2022

Will Nicholes (Invited speaker, Vice-President of Intera, Inc.). Vadose zone modeling of the Hanford site with radionuclides. Use of 3D vadose zone models to predict contaminant transport. Developed custom tools like a recharge evolution tool to provide natural recharge rates. Subsurface transport. Presentation described software and hardware used by Intera, Inc. Liquid and solid waste inventory. Cleanup decision making process of the sites.

<u>Panel #3</u>

- **Fred Zhang**. Intera, Inc. Divergent flow below the deep vadose zone at the Hanford site. Vadose zone considered to be the top 60 to 100 meters. 1D simulations of the Hanford site assuming a fully saturated profile with zero flux and surface boundary condition.

- **Dani Or**. Desert Research Institute**.** Arid region evaporation; soil structure and hydrology. How do we inject soil structure into models? Wildfire effects on soil and hydrologic response. Watershed scale. Surface evaporation capacity. Rainfall partitioning in arid regions ($P/ETref<0.2$). Testing the hypothesis that sheltered storage water that is not evaporated can represent land vegetation capacity.

- **Jirka Simunek.** University of California-Riverside: Work on sprayable biopolymers with groups from Australia and China; Impact of drought and changing water sources on water

use and soil salinity. Work with scientist of Pakistan on the movement of saline water in irrigated tomato. Work in analytical solutions of hydrological models. New Hydrus modules (freezing/thawing module for Hydrus 1D and transport of soil water isotopes. Fate and transport applications of non-ionic surfactant and carbon nanotubes. New Hydrus development, merging Hydrus 1D into Hydrus 2D/3D. New modules of particle tracking modules, cosmic-ray neutron fluxes, surfactants module, a new dynamic plant uptake module, new graphical capabilities for Hydrus.

- **Rose Shillito.** US Army Corps of Engineers: Post-wildfire flood risk management program. Coordinating seven laboratories. Incorporate water repellency on hydrological models. Spatial variability of water repellency. Studying how long does water repellency affect surface runoff after wildfires. What causes soil water repellency? Can we reproduce the soil water repellency? Smoke alone was able to induce soil water repellency. Is soil health a component of models.

- **Doron Kalisman and Tamir Kamai.** Volcani Institute, Israel. Pressure-wave driven wetting ans solute transport in the vadose Zone. Vertical column experiment using pressured water. About 75% more solutes leached with pressure pulses.

- **Discussion:** How long does fire-induced water repellency lsat? In non-fire systems, stress (too dry or too wet) seems to stimulate the biological generation of hydrophobic conditions (comment by David Robinson). Soil health and ecosystem resilience (connect with the work of Asmeret). How do you bridge the gap to validate models with remote sensing data which only measure skin layer soil conditions? We need more insights on the mechanisms controlling soil water repellency (we can probably learn from thin film research. Within the scope of climate change, how can we manipulate the soil surface energy balance to control short wave radiation? (comment by Robert Horton).

<u>Panel #4</u>

- **Scott B. Jones.** Utah State University. Work on machine learning and neural networks to simulate soil water flow. Develop a quantifiable macropore network. 3D printed substrate. Markus Flury suggested using mucilage to mix with the porous media as a growing media in low gravity environments.

- **Manoj Shukla**. New Mexico State University. Brackish groundwater and reverse osmosis concentrate irrigation. How does high salinity irrigation water affects soil health parameters? Sap flow responses to different regimes of salt stress.

- **Markus Tuller.** University of Arizona. Application of deep learning to forecast evapotranspiration from ground and remote sensing observations to aid with real-time estimation of crop water demand. Relationship between short-wave reflectance, plant water potential, and rootzone soil moisture.

- **Thijs Kelleners.** University of Wyoming. Estimation of hillslope hydrology in mountainous region. Determine subsurface hydraulic properties from time-lapse ERT data.

- **Teamrat Ghezzehei.** University of California-Merced. Physics-informed neural networks for data-driven soil modeling. Role of soil structure and water dynamics on microbial respiration. Coupled measurements of soil matric potential and soil respiration using Hyprop device.

Panel #5

- **Scott Bradford**. USDA ARS U.S. Salinity Laboratory in Riverside, CA. Simulations of the fate of virus in porous media. Pore network model to study colloid transport.

- **Steven Evett**. USDA ARS in Bushland, TX. Testing deep profile TDR sensors to determine soil water change in storage compared to weighing lysimeters. New firmware/hardware for node and gateway system for SDI-12 sensor data collection and wireless transmission to field edge.

- **Ole Wendroth.** University of Kentucky. On farm irrigation research in western Kentucky. Determination of field management zones based on clay content and NDVI.

- **Andres Patrignani**. Kansas State University. Development of a new database of soil physical properties for the Kansas Mesonet. Calibration and validation of soil water reflectometers. Measurement of canopy throughfall in turfgrass. Establishment of a new hydrological network in the Konza Prairie.

- **Majdi Abou Najm**. University of California-Davis. Model water repellency. Optimization model for a water-energy-food elements model.

- **Discussion**. How do models account for non-linearity of soil water repellency? How do we measure infiltration in stony soils?

Additional comments and suggestions

Jan Yin proposed to set aside some time for focused discussion on a couple of specific topics that are of interest to most members and are important to consider for future directions/collaborations.

Markus Flury proposed writing a review paper that highlights the most prominent achievements and emerging issues in vadose zone hydrology from the lens of this group. The following topics were suggested:

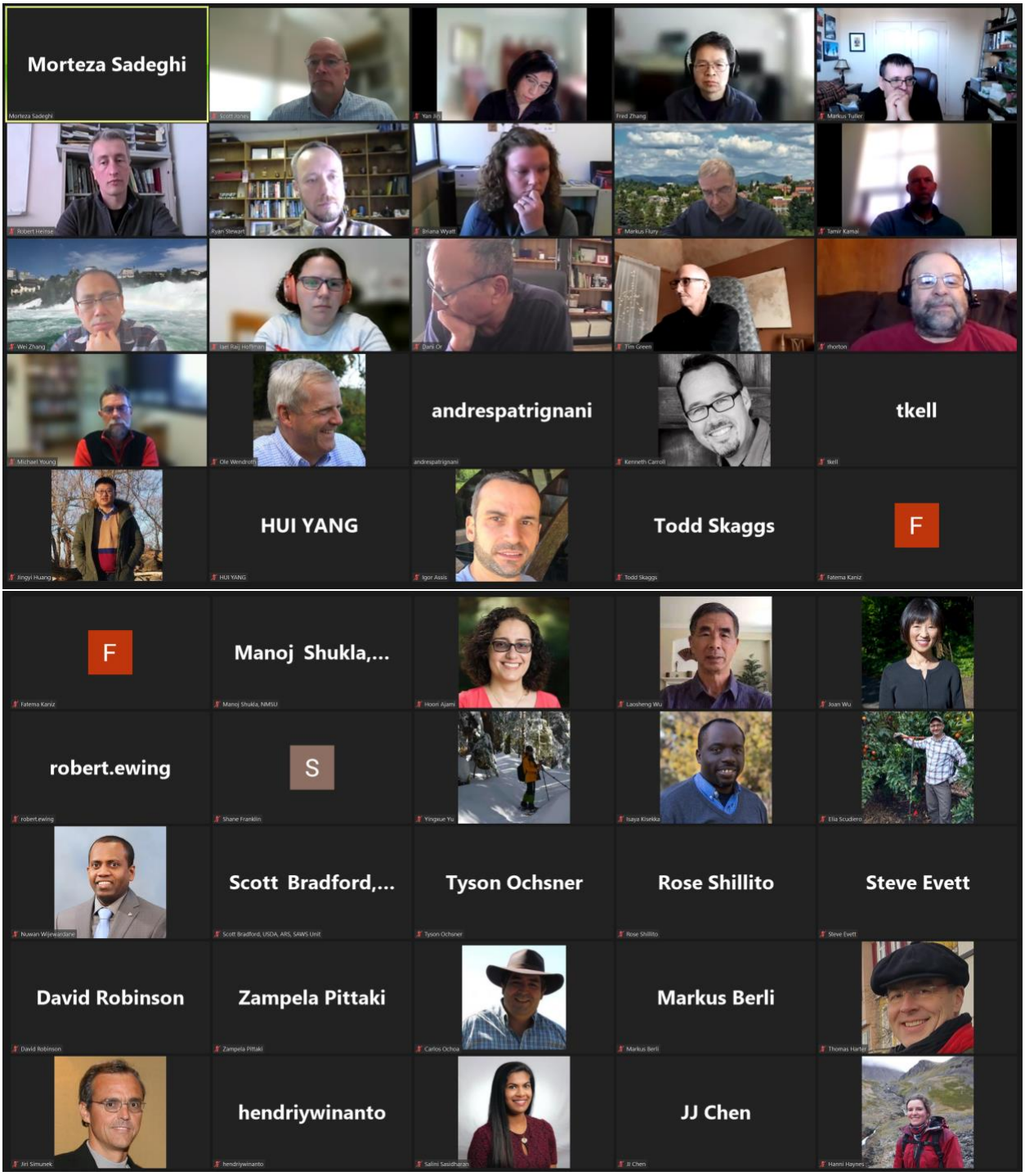
- Historical and forward thinking perspectives
- Carbon dynamic, preferential flow, hot spots, and hot moments
- Fire effects on soil hydrology/vadose zone processes
- Surface energy balance, evaporation, and climate change
- Large scale monitoring of soil moisture (and soil temperature?)

Tim Green suggested to create a special issue that accepts manuscripts related to these topics.
Thij Kelleners proposed to create four special issues, each dedicated to one of the topics above.
Robert Horton mentioned that there was a book written and published by this group called "Soil Water" that we could use as a starting point.
Ole Wendroth suggested a single paper using the Kirkham legacy manuscript as an example:

> Jury, W.A., Or, D., Pachepsky, Y., Vereecken, H., Hopmans, J.W., Ahuja, L.R., Clothier, B.E., Bristow, K.L., Kluitenberg, G.J., Moldrup, P. and Simunek, J., 2011. Kirkham's legacy and contemporary challenges in soil physics research. *Soil Science Society of America Journal*, *75*(5), p.1589.

Tyson Ochsner suggested to create a framework to identify people willing to lead this initiative.
Salini Sasidharan created Slack channel: w4188focusgroup.slack.com
Tyson Ochsner suggested creating a poster session in 2023 to allow for more interaction among participants and decompress oral presentations.

Zoom snapshots provided by Scott Jones: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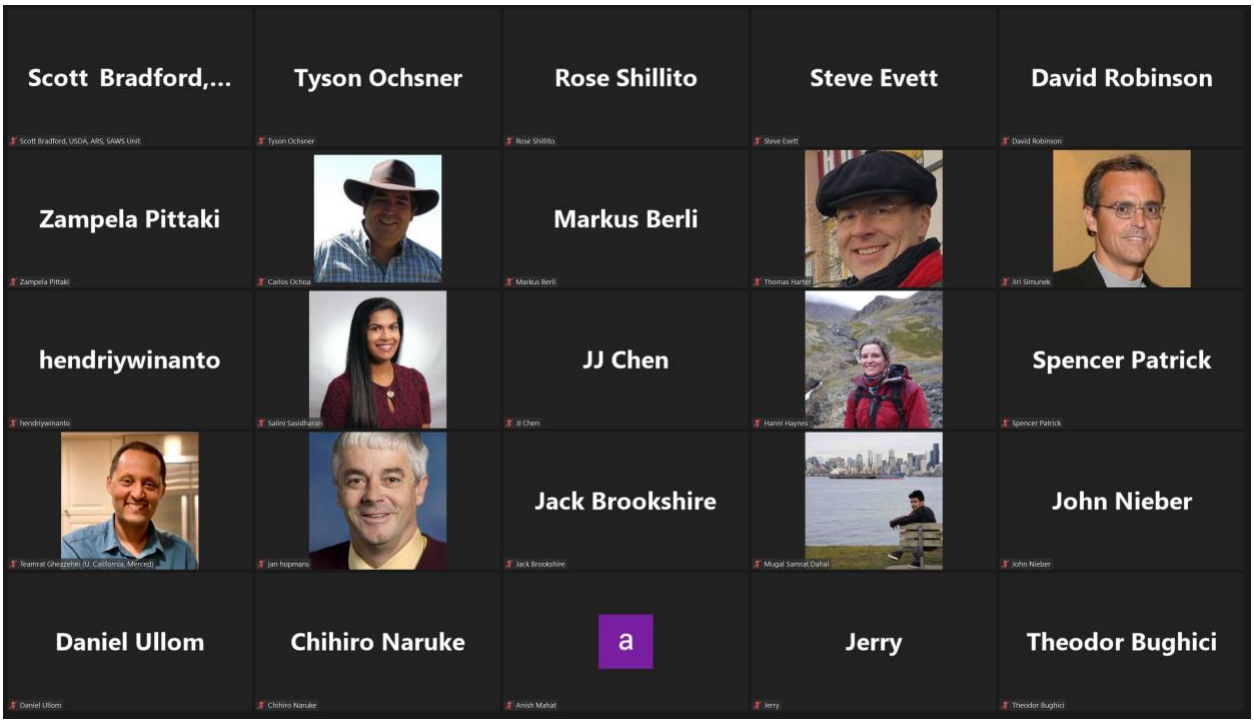
Scott Bradford,...
Scott Bradford, USDA, ARS, SAWS Unit
Tyson Ochsner
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Carlos Ochoa
Markus Berli
Markus Berli
Thomas Harter
Jiri Simunek
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Salini Sasidharan
JJ Chen
Ji Chen
Hanni Haynes
Spencer Patrick
Spencer Patrick
Teamrat Ghezzehei (U. California, Merced)
jan hopmans
Jack Brookshire
Jack Brookshire
Mugal Samrat Dahal
John Nieber
John Nieber
Daniel Ullom
Daniel Ullom
Chihiro Naruke
Chihiro Naruke
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Anish Mahat
Jerry
Jerry
Theodor Bughici
Theodor Bughici

Accomplishments

Short-term Outcomes

Desert Research Institute (Markus Berli)

- A model to describe the relationship between soil hydrophobicity and infiltration
- Methods to determine sorptivity of sub-critically water-repellent soil
- A model to simulate post-fire stream and debris flow

Montana State University (Jack Brookshire)

- We completed analysis of woody plant expansion (WPE) in the Northern Great Plains over the last two decades. Using remote sensing imagery and machine learning models, we determined the degree to which woody plant expansion is contributing to vegetative greening and examined their respective environmental drivers. This paper was submitted in 2021.
- We completed a four-year experiment evaluating the carbon sequestration potential and greenhouse gas implications of bioenergy grass production using alternative cyano-fertilizers. The first paper addressing crop yield and microbial diversity was published (Goemann et al. 2021) and a second paper evaluating soil greenhouse gas responses will be submitted in early 2022.
- We completed experimental work on the long-term effects of WPE and effects of prescribed fire in central Montana. We established a network of permanent vegetation and soil sampling plots and monitored ecosystem process before and after a large prescribed fire. We combine dendrochronology and biogeochemical measures to model the historical (1770- present) consequences of WPE and changes in fire regimes for progressive nutrient limitation of the vegetation carbon sink.
- We completed analyses and published first two papers from a National Center for Ecological Analysis and Synthesis working group on global patterns inorganic nitrogen and dissolved organic matter stoichiometry (Wymore et al. 2021, Rodríquez-Cardona et al. 2022).

University of California Riverside (Hoori Ajami)

- Developed a method to assess the impacts of uncertainty in precipitation and temperature datasets on the water budget of a mountain catchment in the Sierra Nevada
- Quantified groundwater response time including lag time and recovery time to meteorological droughts across the continental US.
- Contributed to the recent review on the dynamic nature of soil structure

Texas Tech University (Sanjit K. Deb)

- Developed and evaluated an algorithm to retrieve soil water content by integrating soil texture into a vegetation index derived from unmanned aerial system multispectral and thermal images
- Developed and evaluated soil-optimized early season planting options under field conditions for cotton germplasms that have been identified to exhibit ≥80% germination ability and seedling vigor in response to low temperature stress under controlled conditions.

- Demonstrated the production and beneficial impact of biochar amendments for vegetable crops under soil- and plant-based deficit irrigation strategies
- Demonstrated the impact of composted animal manure on microbial communities and soil carbon in semiarid improved pasture to provide an additional means of improving soil health and sustainability of perennial pasture systems for livestock production
- Quantified nitrate leaching from bermudagrass and buffalograss established by either seed or sod and irrigated with either tailored or potable water
- Developed equations for predicting Perfluoro alkyl acids (PFAAs) bioconcentration factors (BCFs) for plant shoot and root tissues grown in soils with a known percentage of organic carbon
- Determined the chemical forms of Arsenic (As) in the waste product that is likely to be distributed on soil surfaces and throughout urban and rural areas adjacent to drinking water treatment facilities

New Mexico State University (Kenneth Carroll)

- Developed and compared electrical geophysical methods (resistivity and induced polarization) and temperature sensing methods (fiber optic and high sensitivity sensor) for soil and streambed sediment spatial characterization.
- Quantified sorption and transport behaviors for differing soils and various contaminants (several herbicides and per and polyfluoroalkyl substances (PFAS)).
- Developed method using dissolved gas sampling of groundwater for noble gas isotope analysis for age-dating of groundwater recharge along basin-fill mountain fronts.
- Applied multiple machine learning methods, and obtained predictions of transient oil & gas produced water variability.
- Advised 7 graduate students as Chair. Dr. Carroll had 1 PhD student and 2 MS students that graduated in 2021, and advised 2 postdoctoral researchers and 3 undergraduate researchers.
- Developed international collaborators at China Agricultural University, Nanjing University, China University of Geosciences, Univ. of Bern Switzerland, and Turkish Kocaeli University.
- External grants: $500K

University of California-Davis (Majdi Abou Najm)

- Developed model for (1) infiltration under hydrophobic conditions common after fires; and (2) predicting plant response under different shadings or light treatments. The first model (infiltration) is highly adaptive and can work with any infiltration model (there are more that 70 infiltration models published) and the second model is a first step in developing a modeling framework for agrivoltaics, a leading prospect in agricultural technology.
- Served as the Champion for UC Davis One Climate Big Idea promoting a wide range of soil physical solutions for sustainable water, energy and food systems. I also served as Associate Director for Special Initiatives in the UC Davis John Muir Institute of the Environment promoting a wide range of relevant interdisciplinary research and working on building interdisciplinary teams.
- I am working with exceptional graduate students, currently 8 (in three countries: 2 as chair and 6 as committee member, three awarded during the review period). I hosted 3

visiting scholars (China, Italy, and Spain) and guided research including undergraduate honors these for 5 undergraduate students on different research projects. Involved in different capacities (PI, Co-PI, Collaborator, Significant Personnel) on proposals with a wide range of national and international funding institutions leading to new funding of more than $1.2M through different funds and gifts (including $350k on agrivoltaics and $25 on building life cycle assessment model for working lands).

Utah State University (Scott Jones, Morteza Sadeghi, and David Robinson)

- Scott Jones and Bruce Bugbee at USU continue collaboration on a NASA-funded research grant to improve plant growth media for pick and eat production in reduced gravity conditions. This work has resulted in alternative plant growth media that address issues associated with microgravity including hydraulic discontinuity associated with particulate media as well as nutrient management using water content and electrical conductivity measurements.
- Morteza Sadeghi and Scott Jones collaborated on a Physics-Constrained Machine Learning approach with Mathematics Assistant Professor, Asghar Ghorbani, to develop new soil water flow equations (Ghorbani et al., 2021). With these preliminary results, an internal grant was received to support Dr. Ghorbani's sabbatical at USU to collaborate and further advance this approach.
- David Robinson and Scott Jones continued collaboration with Juando Gonzalez-Teruel, a Spanish Ph.D. Student, in development and application of a custom open-ended dielectric probe (Gonzalez-Teruel et al., 2021) coupled with low-cost network analyzer to obtain the complex permittivity of known dielectrics. This collaboration has further advanced Juando's Ph.D. output with a manuscript under review in *Computers and Electronics in Agriculture*. Juando will come to USU as a visiting Ph.D. student this semester.

University of Wisconsin-Madison (Jingyi Huang)

- Developed machine learning based high-resolution soil moisture model for the globe and continental USA
- Revealed the roles of soil moisture in agricultural and meteorological drought development and early forecasting
- Developed visible near infrared spectroscopy based models and calibration transfer functions for rapid estimating soil water retention curves

North Carolina State University (Josh Heitman) and Iowa State University (Robert Horton)

- We developed approaches to estimate a soil water retention curve from measured soil thermal and electrical properties.
- We developed and tested models that accounted for dynamic effects of water content and bulk density on soil water retention curves and electrical conductivity.
- We developed a pedo-transfer function to estimate how a change in bulk density changes a soil water retention curve.
- We developed a numerical model to quantify surface mulch impacts on soil temperature and water content and on surface water runoff.
- We developed a new heat pulse based sensor to determine soil water content and soil water matric potential.

University of Delaware (Yan Jin)

- Completed the physicochemical characterization of the EPS of *Bacillus subtilis* to help understand the change in hydro-physical properties of bacteria-treated sands.
- Developed the conceptual connection between preferential flow paths and soil carbon dynamics (and more generally, soil biogeochemical processes) and proposed an interdisciplinary path forward in understanding and quantifying biogeochemical interactions at scales of ecological relevance.
- Identified two field sites in Delaware coasts, collected soil and water samples, partially instrumented the field sites for long term monitoring of salinity and redox changes due to flooding and sea-level rise and their effects on soil properties and soil carbon dynamics.
- Improved understanding of how hydraulic redistribution by plant roots affect soil organic matter mineralization and enzymatic activity.
- Demonstrated the critical role of colloid-facilitated transport of weathering elements in controlling stream water chemistry in a long-term monitoring catchment.

University of Kentucky (Ole Wendroth)

- Progressed in the establishment of an on-farm variable-rate irrigation (VRI) system. In 2021, tests were made on the precision of irrigation water application rates, and on a soil water measurement system (Drill & Drop). Irrigation amounts varied between 0.25 and 0.5 inches. In 8 out of 10 cases, nozzles deviated less than 0.09 inches from the intended rate. The largest deviation was found for nozzles close to the center of the pivot system, where nozzle forward speed is lowest and influence of wind largest.

North Dakota State University (Aaron Daigh)

- Established water quality monitoring network in central North Dakota to evaluate linkages between soil microbial community structures and root zone losses of nitrates and phosphate in the vadose zone.
- Evaluated grass species tolerance to cyclical flood-drought, salinization, and submergence to simulate storm water retention zones.
- Developed an algorithm for mapping high-resolution soil moisture across agricultural landscapes in the Red River Valley of the Upper Great Plains region by using machine learning with Landsat 8 imagery, soil characteristic maps, and regional weather mesonets.
- Evaluated a GIS database of landslide conditioning factors in North Dakota, including geologic formations, pore water salinity, inclination, etc.
- Evaluated tillage and cropping systems influence on soil water balances and salinization.
- Evaluated subsurface drainage effects on soil salinity on a no-till field with diversified cropping systems.

Oregon State University (Carlos Ochoa)

- Installed instrumentation to monitor soil moisture, temperature, and conductivity fluctuations in a riparian area, a meadow pasture, a non-irrigated pasture, and an irrigated pasture in western, Oregon.
- Performed data collection and analyses of soil physical properties from various field locations in western, eastern, and central Oregon.

Washington State University (Markus Flury)

- Developed a new methodology to sample micro- and nanoplastic particles from soils, allowing researcher and practitioners to obtain more accurate results on the amounts of plastics in soils

The University of Arizona (Markus Tuller)

- Developed a new deep learning approach to forecast evapotranspiration from ground and remote sensing observations to aid with real-time estimation of crop water demand and irrigation water allocation in agriculture (*Collaborators:* Michigan Technological University and Purdue University Northwest).
- Developed new technique for rapid estimation of soil hydraulic properties based on shortwave infrared imaging and inverse numerical modeling for rapid estimation of soil hydraulic properties. Measurement of wetting curves in the laboratory across the entire soil textural can be completed within 2–3 days and even faster when high performance computing (HPC) is used for inverse modeling (*Collaborators:* Utah State University and Aarhus University).
- Developed time-efficient new method to estimate Atterberg limits of soils from hygroscopic water content. For environmental, agronomic, and engineering applications that require Atterberg limits for a vast number of samples, the new technique is potentially useful as it only requires a RH sensor and a drying oven (*Collaborator:* Aarhus University).

New Mexico State University (Manoj Shukla)

- Irrigation with brackish groundwater and RO concentrate changes soil physical and thermal properties and decreases actual evapotranspiration rates of pecan.
- Demonstrated higher water use efficiency for chile using micro-gravity drip irrigation system.
- Biofertilization with photosynthetic bacteria was shown as a new strategy for mitigating photosynthetic acclimation due to elevated CO2 for cherry tomato. Research was done with China Agriculture University.

Texas A&M University (Briana Wyatt)

- Developed statistical seasonal streamflow forecasting models for irrigation districts and watersheds in OK, KS, and NE to aid in improving surface water management
- Tested novel lithium-foil cosmic ray neutron sensor for estimation of field-scale soil moisture

University of Idaho (Robert Heinse)

- Continued progress on characterizing soil heterogeneity at the Soil Stewards farm. A new graduate student (Danny Baldwin) collected hydraulic and electric conductivities at fine resolution. The data will inform design and operation of small-scale precision irrigation and contribute to outreach and extension activities.
- Continued data analyzes for the Advanced Plant Habitat.
- Initiated work at the Bunker Hill Mine to identify source areas for water intrusions leading to acid-mine discharge.

University of Wyoming (Thijs Kelleners)

- Developed and tested a new inverse modeling framework for estimating subsurface hydraulic properties using geophysics data as part of ongoing NSF-sponsored research
- Summarized advancements in soil salinity monitoring using electromagnetic techniques as part of an upcoming book on soil salinity issues in agriculture

USDA-ARS, Bushland, Texas (Schwartz and Evett)

- New firmware/hardware for node and gateway system for SDI-12 sensor data collection and wireless transmission to field edge followed by upload over cellular telephone network to the Internet was developed by ARS partner and CRADA partner (Acclima). The new firmware includes a "Receiver" mode that keeps the gateway running if the SIM is stolen or cellular service is unavailable, essentially turning the gateway into a master datalogger. The system was used in Jordan on three watersheds and a weighing lysimeter, used in Uzbekistan for irrigation scheduling, used in Texas by ARS and Texas A&M University, and used by state and university Conservation Innovation Grant partners in 21 states.
- Tested deep, dense profiles of TDR sensors to determine soil water change in storage compared with a large weighing lysimeter.
- A new TDR-315N sensor was developed by Acclima with testing at Bushland and released in response to field and laboratory sensor tests that indicated a need for more intelligent waveform processing.
- Sixth year of beta testing of irrigation scheduling supervisory control and data acquisition system was completed in four states, with associated testing of new soil water sensors and wireless infrared thermometers.
- Comprehensive 15-minute quality-controlled microclimate, plant growth, energy and water balance, and soil water content data were shared with Agricultural Model Intercomparison and Improvement Project (AgMIP) maize (2 years) and winter wheat (3 seasons) modeling teams. Maize data were shared with Washington State University and with the OpenET consortium.
- Provided a comprehensive review of the ICARDA/FAO project "Establishing and Operating a Near East and North Africa Regional Network for Evapotranspiration (NENA-ETNet)"

Virginia Tech (Ryan Stewart)

- Developed a new model that accounts for transient water repellency in infiltration processes. This model has been evaluated in two published manuscripts and another manuscript that will soon be submitted.
- Tested different compounds to reduce soil water content and infiltration in vineyard soils as a way to better manage fruit quality.
- Performed field measurements using geophysics (e.g., electrical resistivity tomography) to better understand preferential flow processes.
- Developed a new device to passively collect flow-weighted water samples from surface runoff plots.
- Designed a new system to analyze gas diffusivity in different types and orientations of soils and soilless substrates.
- Conducted a study examining the effects of different sensor housings on water quality sensor performance in streams.

- Trained 2 graduate students, who have used this project framework to collect and analyze data related to their thesis and dissertation work.
- Involved 1 undergraduate student in undergraduate research opportunities.

Oklahoma State University (Tyson Ochsner)

- Seasonal streamflow forecasting methods were developed building on existing, proven streamflow modeling approaches used by the Natural Resources Conservation Service (NRCS). These existing methods were enhanced through the incorporation of remotely sensed soil moisture and terrestrial water storage data, which are increasingly available but thus far not utilized in operational streamflow forecasting. The resulting forecasts explained 35-78% of the variance in streamflow totals for the upcoming season in five watersheds across the US Great Plains.

Kansas State University (Andres Patrignani)

- Use of an exponential filter to estimate rootzone soil water storage in cropland using a single soil moisture sensor near the soil surface.
- Developed a framework for delineating field management zones based on soil moisture observations.
- Reconstructing precipitation using soil moisture information.
- Developed a database of soil physical properties for the Kansas Mesonet

Outputs

U.S. Salinity Laboratory (Todd Skaggs and Ray Anderson)

- Research findings were disseminated via 9 refereed journal publications and several virtual presentations at national and international meetings.
- Updated software for partitioning water and carbon fluxes measured with eddy covariance systems (https://github.com/usda-ars-ussl/fluxpart).
- Newly created web browser application and Github account

Desert Research Institute (Markus Berli)

- Our work focused on experimental and numerical models to describe the water dynamics of arid soils and their impact on desert hydrology with special focus on post-fire conditions.

University of California-Riverside (Amir Haghverdi)

- Two technical journal articles were published focusing on the measurement and estimation of soil hydraulic properties using the HYPROP system and pseudo-continuous pedotransfer function models.
- Multiple presentations were delivered in scientific conferences and extension events focusing on a decision support tool developed by the research team for management zone (MZ) delineation in the southern California desert agriculture region.

- A collaborative international project was started focusing on estimating Stagnosol hydraulic properties and water flow using uni- and bimodal porosity models in erosion-affected hillslope vineyard soils.

Michigan State University (Wei Zhang)

- In 2021 we investigated environmental processes and impacts of engineered nanoparticles, antibiotics, and antibiotic resistance genes (ARGs) in soil, water and plant systems. We published 4 journal articles and gave 3 conference presentations.

Montana State University (Jack Brookshire)

- We published five papers and submitted five others to peer-reviewed journals.

University of California Riverside (Hoori Ajami)

Research findings were disseminated via:

- 5 publications in peer-reviewed journals
- 1 research report about Salton Sea hydrology
- 17 conference abstracts and presentations and 3 invited talks
- Taught 1 upper division undergraduate course on Spatial analysis and remote sensing for environmental sciences (4 units), and an undergraduate course in Principles of Groundwater Science (4 units).
- Served in 3 PhD dissertation committee and participated in 8 PhD qualifying exams
- Served as an Associate Editor of California Agriculture, Hydrological Sciences Journals, and Journal of Hydrology

Texas Tech University (Sanjit K. Deb)

Research findings were disseminated via:

- 13 publications in peer-reviewed journals
- 10 conference abstracts and presentations
- research reports

New Mexico State University (Kenneth Carroll)

Research findings were disseminated via:

- 9 publications in peer-reviewed journals
- 1 conference proceedings paper
- 13 conference abstracts and presentations
- Dr. Carroll chaired a symposia and a session at SSSA (both including poster and oral)
- Web postings (ResearchGate, Twitter, LinkedIN, scienceofsoil.com)
- Monthly Science Café webinar presentation series for Sigma Xi chapter
- Terri Cook (2021) Parsing Routes to Aquifer Recharge Along Mountain Fronts. 8 Feb. https://eos.org/research-spotlights/parsing-routes-to-aquifer-recharge-along-mountain-fronts (Press Release in AGU's EOS)

University of California-Davis (Majdi Abou Najm)

Research findings were disseminated via:

- 6 publications in peer-reviewed journals

- 13 abstracts and conference proceedings including 6 invited talks.

Utah State University (Scott Jones, Morteza Sadeghi, and David Robinson)

- Research results were disseminated in collaboration with colleagues in the US, Iran, Spain, UK and China through 19 peer-refereed international journal publications, 3 conference proceedings and 11 conference oral/poster- or invited talk-contributions.
- Developed novel resource supply, monitoring and control approaches for the plant root-zone in the microgravity environment including novel plant growth media based on fibrous structure to reduce particle separation and maintain hydraulic continuity.

University of Wisconsin-Madison (Jingyi Huang)

Research findings were disseminated via:

- 7 publications in peer-reviewed journals
- 8 conference abstracts and presentations

Texas A&M University (Binayak Mohanty)

Research findings were disseminated via refereed journal publications, conference proceedings, and a number of presentations at national and international meetings (see the publication section below). Developed and managed the operation of Texas Water Observatory on Brazos River Basin in Texas, a testbed for better understanding of coupled water, carbon, and energy cycle at different scales.

North Carolina State University (Josh Heitman) and Iowa State University (Robert Horton)

Research findings were disseminated via:

- 30 publications in peer-reviewed journals
- 1 research report
- 25 conference abstracts and presentations

University of Delaware (Yan Jin)

- Research findings were disseminated through a peer-reviewed review article in *Soil Biology and Biochemistry* and 7 invited or volunteered presentations at national and international conferences.
- Results from the rhizobacteria project were presented at the 2021 InterPore conference and a manuscript is in advanced stage of preparation.
- Publication of review paper in Soil Biology and Biochemistry
- Presentation at the 5th Summer School on Flow and Transport in Porous and Saturated Media. Carges, France. July
- Oral presentation at SSSA discussing the outlook of upscaling pore scale carbon dynamics
- One volunteered poster presentation in the SSSA meeting. We also presented our data in an internal meeting among different groups for the University of Delaware, ERDC and Louisiana State University
- We presented our findings at SSSA annual meeting 2021, tilted with “Root redistributes water for soil organic matter mineralization in the rhizosphere”.

- We presented our findings at AGU fall meeting 2021, tilted with “Insights into colloids-mediated transport in catchments: a metadata analysis”.

University of Kentucky (Ole Wendroth)
Research findings were disseminated via:

- publications in peer-reviewed journals
- research reports
- Meetings with commodity groups
- proposal for project funding support to NIFA

North Dakota State University (Aaron Daigh)
Research findings were disseminated via,

- 11 publications in peer-reviewed journals
- 4 research reports
- 14 conference abstracts and presentations

Oregon State University (Carlos Ochoa)

- Six publications in peer-reviewed journals
- One book chapter
- One conference proceedings publication
- Two national meeting abstracts
- Conference contribution presenting soil moisture monitoring in three long-term, watershed-scale, studies in northern Mexico and in western, central, and eastern OR locations.

Washington State University (Markus Flury)
Research findings were disseminated via:

- 12 publications in peer-reviewed journals
- 8 conference abstracts and presentations

The University of Arizona (Markus Tuller)
Research findings were disseminated via:

- 11 Publications in peer-reviewed journals
- 5 Conference abstracts and presentations

New Mexico State University (Manoj Shukla)

- Research results were disseminated in collaboration with various involved groups through 9 peer-reviewed journal articles, 7 conference contributions, and interactions with stakeholders and growers.
- A new IOT system installed in Leyendecker Plant Science as a new Digital Agriculture hub.
- Taught a Course on Digital Agriculture in University of La Salle, Bogota, Colombia.

Texas A&M University (Briana Wyatt)
Research findings were disseminated via:

- 1 publications in peer-reviewed journals
- 3 conference abstracts and presentations

University of Idaho (Robert Heinse)
Research findings were disseminated via:
- 2 publications in peer-reviewed journals
- 1 research reports
- 3 conference abstracts and presentations

University of Wyoming (Thijs Kelleners)
Research findings were disseminated via:
- 1 paper published in the journal Geophysics
- 1 paper in review with the journal Water Resources Research
- 1 book chapter in review
- 1 presentation for the soil physics W4188 multi-state research project

University of California-Riverside (Jirka Šimůnek)
Research findings were disseminated via refereed journal publications, conference proceedings, and presentations at national and international meetings (see the publication section with 31 peer-reviewed journal articles below). HYDRUS models have been updated with several new capabilities and options that have been developed for various research projects, which in turn have been published in peer-reviewed journals. Additionally, we have added new capabilities to HYDRUS to rigorously consider the transport of PFAS in the vadose zone, to simulate cosmic-ray neutron fluxes, the particle tracking algorithm to assess water travel times, etc.

USDA-ARS, Bushland, Texas (Schwartz and Evett)
- The 2020 revised commercial version of the ARS node and gateway system from CRADA partner Acclima was tested during the February 2020 three-week polar vortex incursion of severe weather in Texas and was shown to work reliably in temperatures of -21 °C, and temperatures <-8 °C for eight days (one gateway, six nodes, and 36 sensors).
- CRADA partner Acclima introduced new TDR-315N and TDR-310N sensors with more intelligent waveform processing with testing at Bushland.
- CRADA partner USDA ARS, Beltsville, MD, improved node and gateway firmware to allow connection of additional SDI-12 sensors, including Apogee infrared sensors, and the METER ATMOS all-in-one weather station. The gateway firmware was enhanced with a “Receiver” mode that allows the gateway to continue operation as a master datalogger if the SIM is stolen or cellular service is unavailable. The node and gateway hardware and firmware allow inexpensive, low-power (solar powered) collection of data from SDI-12 sensors (e.g., CS655, TDR-315N, TDR-310N, SapIP-IRT, Apogee IRT, ATMOS weather station) and transmission from node to gateway using LoRa radio protocol across cropped fields and from gateway to the Internet via cellular telephony.
- Training was provided to Texas A&M University staff in installation, configuration, troubleshooting, and data handling of soil water data from Acclima solar-powered node and gateway SDI-12 sensing and telemetry systems, with a focus on projects at College Station. Training materials are available at

https://drive.google.com/drive/folders/1TykcXI2zyyd-rRGrZ2bSPcRWW4UmXMkX?usp=sharing

- Published 7 peer reviewed journal articles, and two formal reports in 2021.
- Our team made 10 invited and 12 volunteered presentations in 2021

Virginia Tech (Ryan Stewart)
Research findings were disseminated via:

- 8 publications in peer-reviewed journals
- 2 research reports
- 18 conference abstracts and presentations

Oklahoma State University (Tyson Ochsner)
Research findings were disseminated via:

- 2 conference abstracts and presentations
    - Wyatt, B.M., T.E. Ochsner, M. Wang. 2021. Improving seasonal streamflow forecasts for surface water irrigation districts by incorporating soil moisture information derived from remote sensing. ASA, CSSA, SSSA International Annual Meeting, Salt Lake City, Utah, Nov. 7-10, 2021.
    - Wyatt, B. M., Ochsner, T. E., & Wang, M. Improving Seasonal Streamflow Forecasts for Surface Water Irrigation Districts By Incorporating Soil Moisture Information Derived from Remote Sensing. In *AGU Fall Meeting 2021*. AGU.

Kansas State University (Andres Patrignani)
Research findings were disseminated via:

- 6 Agricultural Experiment Station Annual reports
    - Dyer, W*., Bremer, D., Rossini, P*., Stone, M**., and Patrignani, A. 2021. Laboratory Calibration of the Spectrum Field Scout TDR 300. Kansas Agricultural Experiment Station Research Reports: Vol. 7: Iss. 4. https://doi.org/10.4148/2378-5977.8070
    - Flory, J.**; Grane, J*., and Patrignani, A. 2021. Using a Sprayable Biodegradable Polymer to Reduce Soil Evaporation in Greenhouse Conditions. Kansas Agricultural Experiment Station Research Reports: Vol. 7: Iss. 5. https://doi.org/10.4148/2378-5977.8079
    - Parker, N.* and Patrignani, A. 2021. Evaluating Traditional and Modern Laboratory Techniques for Determining Permanent Wilting Point. Kansas Agricultural Experiment Station Research Reports: Vol. 7: Iss. 5. https://doi.org/10.4148/2378-5977.8080
    - Nahitiya, D.*, Bisheh, M. N.*, Lollato, R. P., and Patrignani, A. 2021. Preliminary Classification of Soil, Plant, and Residue Cover Using Convolutional Neural Networks. Kansas Agricultural Experiment Station Research Reports: Vol. 7: Iss. 5. https://doi.org/10.4148/2378-5977.8081
    - Rossini, P.* and Patrignani, A. 2021. On-Farm Assessment of AquaSpy Soil Moisture Sensors for Irrigation Scheduling. Kansas Agricultural Experiment Station Research Reports: Vol. 7: Iss. 5. https://doi.org/10.4148/2378-5977.8082
    - Parker, N.* and Patrignani, A. 2020. A Pilot Experiment to Replace Missing Rainfall Events Using Soil Moisture Information from the Kansas Mesonet.

Kansas Agricultural Experiment Station Research Reports: Vol. 6: Iss. 5. https://doi.org/10.4148/2378-5977.7918

- 6 peer-reviewed manuscripts
- 3 Conference presentations

Activities

Desert Research Institute (Markus Berli)

- Developed a physically-based model to describe the relationship between soil hydrophobicity (expressed as apparent contact angle or water drop penetration time) and infiltration through sorptivity
- Evaluated methods to measure sorptivity of sub-critically water-repellent soil in the field
- Worked on an improved understanding of water infiltration, redistribution and evaporation from arid soils

Funding:

- USACE-UFDP: Simulating post-fire streamflow in a desert urban system (continuation)
- DOE-LM: Surface Cover Assessment of the Mexican Hat Disposal Site, Utah (continuation)
- NSF-RAPID: Evaluation of post-wildfire effects on soil physical and chemical properties in response to the Tamarack fire near Lake Tahoe: A pilot field study

University of California-Riverside (Amir Haghverdi)

The UCRWATER team developed a satellite-based agriculture management zoning tool for the southern California desert agriculture region, called "SAMZ-Desert". This tool is a web-GIS-based interactive tool that shows Landsat-NDVI-based MZs for all the fields in southern California. This tool was developed for end-users and growers with no experience and expertise required to obtain the results for individual fields. The users only need to find their fields (using a google map embedded in the tool), click on the map and see the results. All the complicated remote sensing and statistical analysis steps happen behind the scene. The UCR water team also finished developing two international neural network-based pseudo-continuous pedotranfer functions ($PC_{NN}PTF$) and started a collaborative project with researchers in Europe aiming at adequate identification of hydropedological factors that influence soil water dynamics in erosion-affected and intensively managed agroecosystems.

Michigan State University (Wei Zhang)

Our research primarily focused on the fate and transport of emerging contaminants in soil, water, and plant systems. In addressing Objective 1, we completed the studies on internalization of silver nanoparticles through plant leaf stomata. We also completed the study on bacterial community assembly and profiles of ARGs in lettuce shoots and roots, rhizosphere soil, and bulk soil irrigated with antibiotics-containing water, using high throughput qPCR and 16S rRNA amplicon sequencing techniques. Specifically, we examined the transport of antibiotics in the continuum of bulk soil, rhizosphere soil, roots, and shoots of lettuce. The papers summarizing these results are in press. We are continuing studying the interactions of infectious proteinaceous particles (prions, new groups of emerging contaminants) with soil geosorbents. This study aimed to understand environmental behaviors of chronic wasting disease prions and to develop novel

cost-effective mitigation strategies. We established molecular dynamics simulation capacity to study interactions of amino acids, and eventually with peptides, polypeptides, and prions.

University of California Riverside (Hoori Ajami)

- Improving vegetation parameterization in integrated groundwater-land surface models
- Improving mountain system recharge predictions in the Sierra Nevada California
- Characterizing mountain flow path using geochemical data and mixing models
- Assessing the role of subsurface heterogeneity on controlling groundwater response time to droughts
- Identifying major drivers of hydrologic change in the Salton Sea basin

Texas Tech University (Sanjit K. Deb)

- Completed the 2021 growing season field experiments and modeling tasks on evaluating root zone soil water dynamic under various agronomic practices/conditions in semiarid environments (*TSSC-Cotton Incorporated funded project, PI*), including (i) evaluating root water uptake of cotton under deficit subsurface drip irrigation, (ii) evaluating soil water dynamics in cotton production systems using numerical model HYDRUS (2D/3D) and agricultural system model RZWQM2, (iii) evaluating root zone soil water dynamics under cotton-weed interactions, and (iv) evaluating effects of early season planting and soil physical environments on physiological responses and quality of cotton germplasms with cold germination ability.
- Completed preliminary modeling tasks on evaluating GHG emissions under different pasture management practices and evaluated mitigation scenarios that optimize resource use and productivity (*USDA-NIFA-AFRI funded project, Co-PI*)
- Completed the 2021 season field experiments on evaluating production and beneficial impact of biochar amendments for cotton germplasms with cold germination ability and vegetable crops under soil- and plant-based deficit irrigation strategies (*TSSC-Cotton Incorporated funded, PI;* and *SCBGP, USDA, Co-PI*)
- Completed preliminary field and lab experiments and numerical modeling tasks on the coupled energy-water-isotope transport in vadose zone of natural rangeland in semiarid environment
- Completed undergraduate research project on the effects of long-term perennial and annual pasture systems on soil physical quality indicators in the semiarid Texas Southern High Plains
- Advised one Ph.D. student, three M.S. students, and one undergraduate researcher as chair; advised one PhD student and one M.S. student as co-chair; served on five Ph.D. and three M.S. students' committees; and served as faculty associate/supervisor for one Fulbright Visiting Scholar
- Taught graduate course PSS 5335 Soil Physics (*cross-listed* undergraduate course PSS 4336 Soil Physical Properties) in two modalities (face-to-face and distance education)
- Acted as Associate Editor (one journal), served as Guest Editor (one), and served as reviewer for peer-reviewed international journals

New Mexico State University (Kenneth Carroll)

- Completed solute transport lab experiments and modeling
- Completed noninvasive geophysical and temperature sensor methods for hyporheic zone

characterization
- Applied multiple machine learning methods to predict transient oil & gas produced water variability
- Developed/applied method using dissolved gas sampling of groundwater for noble gas isotope analysis for age-dating
- Organized monthly Science Café webinar presentation series for Sigma Xi chapter
- Acted as Associate Editor for 3 peer-review international journals and completed additional manuscript reviews

University of California-Davis (Majdi Abou Najm)

- Development of an adaptive model for infiltration of water-repellent soils: This is a one-parameter model that can be added to any of the infiltration models to account for water repellency or hydrophobic behaviors. Model was tested with more than 100 infiltration experiments and showed major improvements in predicting infiltration as compared to current models.
- Development of a modeling framework for predicting plant response to light: This is a new model that predicts transpiration, water use efficiency, stomatal opening and carbon assimilation under different light treatments. This is needed to establish a modeling framework under agrivoltaics systems.
- Conduct a critical review on soil infiltration: we are tracing the evolution of infiltration theory that led to the development of more than 70 unique infiltration models over the past 2 centuries with the objective of identifying barriers and challenges, as well as recommending a roadmap for future directions.
- Systematic review on how does soil structure affect infiltration: we collected data from around 800 unique plots with different treatments and are conducting a systematic review on the impact of those treatments on soil structure and infiltration capacity.

Utah State University (Scott Jones, Morteza Sadeghi, and David Robinson)

- Design, Monitoring and Management for Optimizing Water, Nutrients and Gas Exchange within the Root-Zone Environment in Microgravity. USU (Jones and Bugbee) continued work to develop novel resource supply, monitoring and control approaches for the plant root-zone in the microgravity environment of the International Space Station (ISS). Our approach is based on decades of research in i) root-zone definition and modelling for microgravity, ii) optimizing water, nutrient and oxygen delivery to plant roots in semi-closed systems, and iii) flight hardware development and testing including past flight experiments on the Russian MIR Space Station (GEMS) and on the ISS (LADA, ORZS). Supported by the National Aeronautics and Space Administration under Grant No. 80NSSC20K1411 issued through the (NNH18ZTT001N-PT) Appendix C: Development of Microgravity Food Production: Plant Watering, Volume Management, and Novel Plant Research on the International Space Station."
- Standardization of electromagnetic measurements of soil moisture. Electromagnetic sensor standards development work continued using coarse granular media as a test and calibration standard with colleagues from the UK, Spain, China, Israel and Poland. This work is supported by the Polish National Agency for Academic Exchange, grant number: PPI/APM/2018/1/00048/U/001.

- Serving Utah's Diverse Land Management Needs with a High-Resolution Sub-Seasonal Forecasting Platform. (*Jon Meyer, Brennan Bean, Scott B. Jones, Wei Zhang* and *Rob Gillies*). The Utah Climate Center continued development of resources in terms of short-term state-wide weather forecasting and soil moisture mapping with web-based resource development. Several proposals were submitted to USDA and BARD to develop improved regional weather forecasting for agricultural applications.

University of Wisconsin-Madison (Jingyi Huang)

- Worked on one research project funded by USDA Hatch - Multistate W4188: Mapping surface soil water dynamics at fine spatial and temporal resolutions across the U.S. Climate Reference Network using Sentinel-1 and ancillary data
- Advising one post-doctoral researcher, two Ph.D. students, one M.S. student, and three undergraduate students and serving on the committee members of three Ph.D. student. students
- Teaching Soil Physics (Soil Science 622), Physical Principles for Soil and Water Management (Soil Science 322), and Using R for Soil and Environmental Sciences (Soil Science 585)
- Reviewed 60 manuscripts for various journals

Texas A&M University (Binayak Mohanty)

In 2021, field monitoring and laboratory experiments were conducted at Texas Water Observatory sites under different land use land covers for improved understanding of soil moisture, temperature, and carbon dynamics and soil hydraulic and retention properties variation from local, regional, to global scale. Using soil monitoring stations, Eddy Covariance towers, SMAP satellite and International Space Station (ECOSTRESS) observations, and improved process modeling concepts, we developed new soil moisture and ET retrieval, dry-down patterns, flash drought outlook, scaling, fusion, gap-filling, and forecasting techniques at multiple space-time scales. In addition, we measured soil hydraulics in different land covers and landscape positions and studied the linkages between surface water, ground water and vadose zone with bidirectional exchange schemes. Saturated hydraulic conductivity and ground water recharge estimation frameworks were developed using machine learning tools and dominant geophysical controls.

Meeting organized:

- Session Chair on Land-Atmosphere Interactions: From Bedrock to Boundary Layer I, American Geophysical Union Fall Meeting, New Orleans (2021)

Meetings attended:

- American Geophysical Union Fall Meeting, December 13-17, 2021.
- Invited Speaker, Water Below your Feet: Significance, Challenges, & Opportunities, Texas Water Brigade, *University of Texas Austin*, Online, February 12, 2021.
- Invited Speaker, Physics Augmented Artificial Intelligence for Agriculture and Natural Resources: The Challenges and Opportunities, *IEEE-RSJ International Conference on Intelligent Robots and Systems (IROS)*, Prague, Czech Republic, Online, September 27, 2021.

- Keynote Speaker, Soil Moisture – State-of-the knowledge: Measurement, Variability, Physical Controls, and Data Fusion, *XXIV Brazilian Water Resources Symposium*, Brazil, Online, November 24, 2021
- Invited Lead Speaker, Estimating High Resolution Soil Moisture and Hydraulic Properties for Sustainable Agriculture, *5th International Agronomy Congress*, Hyderabad, India, Online, Nov 25, 2021.

Funding:

- USDA-ARS (Agricultural Research Service): Establishing the Texas A&M Texas Water Observatory (TWO) and USDA-ARS Partnership at the Riesel Watersheds, Riesel, Texas, 10/16-09/21; Total Amount - $130,000
- NASA-SUSMAP (Science Utilization of the Soil Moisture Active-Passive Mission): Root Zone Soil Hydraulic Property Estimation by SMAP, 10/16-09/21, Total Amount - $379,022
- NASA-SMAP-ST (Soil Moisture Active Passive Science Team): SMAP Science using Multi-Scale Data Fusion: Forecasting Flash Drought to Flash Flood, 09/20-09/23, Total Amount - $459,035
- Industry: Tracking Root Zone Contaminants in Agricultural Farms near Texas Superfund Sites, – 09/21-08/25, Total Amount - $686,481

<u>North Carolina State University (Josh Heitman) and Iowa State University (Robert Horton)</u>

- We developed approaches to estimate a soil water retention curve from soil thermal and electrical properties.
- We evaluated and optimized the performance of constructed thermal property sensors in the presence of roots by accounting for the influence of the roots.
- We used measurements to calibrate and validate new models of soil electrical conductivity and hydraulic conductivity.
- We evaluated the biomass yield and water use efficiency of perennial and annual bioenergy crops in urban soils.
- We tested plant seed germination responses to different water availability conditions.
- We measured the impact pipeline installation soil disturbance on corn and soybean growth.

<u>University of Delaware (Yan Jin)</u>

- Preparing the manuscript on how different physico-chemical properties of the EPS of *Bacillus subtilis* are correlated to the bacteria's ability to enhance soil water retention.
- Designed new experiments using longer (than HYPROP cells) to more completely delineate the varying characteristic evaporative length and critical evaporation phase transitions to improve mechanistic understanding of bacterial EPS enhanced hydro-physical properties of soil.
- Collected field samples in collaboration with the U.S. Army Engineer Research and Development Center (ERDC) Environmental Laboratory and the Louisiana State University for detailed characterization of the soil chemical, physical, and hydraulic properties.

- Completed laboratory set-up with new HYPROPS, K_{sat}, WP4C instruments and developed standard protocols for measuring saturated and unsaturated hydraulic conductivity over a wide range of wet and dry soil conditions.
- Purchased and calibrated Pt-redox probes, dataloggers, and LTC sensors for *in-situ* monitoring of the soil redox potential, salinity, water level, and temperature in field sites.
- Installed piezometers and standard monitoring wells along a salinity and redox gradient at four field locations in the St. Jones Reserve in Delaware to collect and monitor pore water samples over a long term (3 years).
- Developed experimental system to study the functional implications (carbon cycling) of soils with macropores and preferential flow.
- Proposed and presented experimental plan and design in the ACTIONS (Anticipating Project Virtual Conference on September 8-10, 2021, and DOD Research University of Delaware Team Meeting held on December 14, 2021. The team members reviewed the plans and updates.
- Purchased and installed different laboratory and field instruments, e.g., HYPROPS, Ksat, WP4C, centrifuge, sediment soil core sampler, Pt redox probe, LTC sensor etc
- Measured soil water retention curves, saturated and unsaturated hydraulic conductivity using HYPROPS, Ksat, and WP4C instruments.
- Collected eight 48" long intact soil core samples from four field locations along a redox gradient in St. Jones Reserve to study the Fe-mediated fractionation of soil organic C.
- Conducted experiments that simulated the processes of hydraulic redistribution in rhizobox to investigate how soil organic matter mineralization is affected by root wetting and drying cycles
- Performed a metadata analysis of stream water chemistry using data from a long-term monitoring catchment to identify the role of colloids in facilitating transport of weathering elements.

University of Kentucky (Ole Wendroth)

- An on-farm double-crop soybean field was irrigated with the variable rate system with different rates, while soil water content was measured throughout the growing season with the goal to see spatial differences in soil water dynamics and soybean yield. This analysis is not completed yet. Technical problems had to be overcome caused by cables twisting up. We are learning the use of the variable rate system's software, the production of VRI application maps and different types of system controls.
- Currently, we are preparing for technical details in the use of UAV- and satellite-based remote sensing for variable-rate-nitrogen application (VRN) in a farmer's field.

North Dakota State University (Aaron Daigh)

- Long-term research plots (established in the 1980s) and nine farmer fields were instrumented with lysimeters to monitor solution nitrate and phosphate below the root zones. Soil samples were also obtained to characterize the soil microbial community structures.
- Seven ornamental grass species were grown and monitored in the greenhouse to evaluate species tolerances and ability to remediate petroleum contamination under various water and saline conditions.
- Six machine learning models were further compared for integrating satellite imagery, soil

characteristics, and weather station data to predict high-resolution mapping of soil moisture across the Red River Valley. An algorithm and workflow was developed. The algorithm was validated and tested against measured data.

- A GIS database was further constructed of >24,000 landslides in North Dakota, soil salinity, geology, topography, etc. maps. Data analysis was performed to characterize landscape conditioning factors that are associated with landslides in this region.
- Soil water contents, water tables, crop development, and meteorological data were collected at an on-farm research site. This experiment is designed to improve our understanding of cover crop and tillage effects on the soil water balance in agricultural fields with seasonally frozen soils.
- Crop were again planted and their production evaluated on a coalmine reclamation site where soil has been respread, contoured, and then treatments of deep ripping, mulching, and amending with a super absorbent polymer (SAP) imposed to aid in alleviating soil compaction.
- Water table depths and major salt ion concentrations, soil salinity, and crop yields were measured on a long-term research site that is being used to evaluate subsurface drainage.

<u>Oregon State University (Carlos Ochoa)</u>

- Investigated soil water relations in irrigated and non-irrigated pastures to assess water and nutrient transport through the vadose zone and into the shallow aquifer [Collaboration with D. Godwin and S. Ates (OSU)].
    - Field and laboratory work related with soil physical properties and water transport through the unsaturated zone.
- Investigated soil water relations in juniper-sage steppe landscapes to assess water transport through the vadose zone and into the shallow aquifer.
    - Automated field data collection at multiple locations in one watershed with juniper and one where juniper was removed 15 years ago.
- Investigated soil water relations in flood-irrigated pasture fields in New Mexico to determine water transport through the vadose zone and into the shallow aquifer [Collaboration with S. Guldan and A. Fernald (NMSU)].

Funding:

- Agriculture and water quality indicators in the Willamette Basin: Long-term project. OSU-CAS Legislature Funding. Continuous Funding. 2021- 2026 cycle. $100,000/yr. C. Ochoa and D. Godwin.
- A systems-based understanding of rangeland watershed-riparian systems in eastern Oregon. Oregon Beef Council. 2021-2022. $18,000. C. Ochoa.

<u>Washington State University (Markus Flury)</u>

- Organized symposium on emerging pollutants in soil and groundwater systems at the EGU meeting in April 2021
- Served as Editor of Vadose Zone Journal
- Served as Guest-Editor for a special issue on microplastics in terrestrial systems for Science of the Total Environment

<u>The University of Arizona (Markus Tuller)</u>

- Forecast of Evapotranspiration from Ground and Remote Sensing Observations with Deep Learning *(Univ. of Arizona[1], Michigan Technological Univ.[2], and Purdue Univ. Northwest[3]; Ebrahim Babaeian[1], Sidike Paheding[2], Nahian Siddique[3], Vijay K. Devabhaktuni[3], and Markus Tuller[1])*: Evapotranspiration is a key component of the hydrologic cycle. Accurate short-, medium-, and long-term forecasts of actual evapotranspiration (ET_a) are crucial not only for quantifying the impacts of climate change on the water and energy balance, but also for real-time estimation of crop water demand and irrigation water allocation in agriculture. Despite considerable advances in satellite remote sensing technology and the availability of long ground-measured and remotely sensed ET_a time series, real-time ET_a forecasts are deficient. We applied a state-of-the-art deep learning (DL) approach to develop Long Short-Term Memory (LSTM) models to nowcast (real-time) and forecast (ahead of time) ET_a based on meteorological and ground-measured (i.e., soil moisture) input variables as well as long ET_a timeseries from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard of the NASA Aqua satellite. Conventional LSTM and convolutional LSTM (ConvLSTM) DL models were developed for seven distinct climatic zones across the contiguous United States. The developed LSTM and ConvLSTM models were trained and evaluated with data from the National Climate Assessment-Land Data Assimilation System (NCA-LDAS) and with MODIS/Aqua Net Evapotranspiration MYD16A2 product data. Various meteorological variables were tested for ET_a forecasting with conventional LSTM. The obtained results indicate that when a variety of input variables for the conventional LSTM models are used, they yield accurate daily ET_a forecasts for short (1, 3, and 7 days) and medium (30 days) time scales. At the watershed scale, the ConvLSTM models yielded accurate weekly spatiotemporal ETa forecasts with higher computational efficiency for various climatic conditions. The developed models enable precise forecasts of both the current and future states of ET_a, which is crucial for understanding the impact of climate change on rapidly depleting water resources.
- Information Depth of NIR/SWIR Soil Reflectance Spectroscopy *(Univ. of Tehran[1], Utah State Univ.[2], Univ. of Arizona[3]; Sarem Norouzi[1], Morteza Sadeghi[2], Abdolmajid Liaghat[1], Markus Tuller[3], Scott B. Jones[2], Hamed Ebrahimian[1])*: Proximal and remote sensing techniques in the optical domain are cost-effective alternatives to standard soil property characterization methods. However, the extent of light penetration into the soil sample, also termed soil information depth, is not well understood. We developed a new analytical model that links the particle size distribution and soil reflectance in the near infrared (NIR) and shortwave infrared (SWIR) bands of the electromagnetic spectrum. The model enables the partitioning of measured reflectance spectra into surface and volume (subsurface) contributions, thereby yielding insights about the soil information depth. The model simulations indicate that the surface reflectance contribution to the total reflectance is significantly higher than the volume reflectance contribution for a broad range of soils that vastly differ in texture, mineralogical composition, and organic matter contents. The results reveal an intimate physical relationship between soil reflectance and the particle size distribution in the NIR/SWIR range, which opens a potential new avenue for retrieval of the particle size distribution from remotely sensed reflectance via a universal process-based approach.
- Estimating Atterberg Limits of Soils from Hygroscopic Water Content *(Aarhus Univ.[1], Univ. of Arizona[2], Aalborg Univ.[3]; Emmanuel Arthur[1], Hafeez Ur Rehmana[1], Markus*

Tuller[2], Nastaran Pouladi[1], Trine Nørgaard[1], Per Moldrup[3], Lis Wollesen de Jonge[1]): A vast number of environmental, agronomic, and engineering applications require knowledge of the Atterberg limits and the plasticity index of soils. The expense of standard experimental methods, as well as challenges with measurement repeatability motivated the development of a new method to estimate the Atterberg limits from hygroscopic water content. The new technique is quite powerful as it only requires a RH sensor and a drying oven.

New Mexico State University (Manoj Shukla)

- We conducted CO_2 elevation experiment combined different water regimes and inoculation with photosynthetic bacterium, to evaluate the improvement of photosynthesis acclimation by using photosynthesis bacteria, and to explore associated mechanisms for artificial chamber grown cherry tomatoes. As a result of these experiments, we found that elevated CO_2 had a positive effect on cherry tomato photosynthetic activity and yield of all treatment. Inoculation with the photosynthetic bacteria diminished the yield penalties caused by the reduced irrigation treatment through promoting nitrogen content and relieve starch accumulation in tomato leaves compared to those of the uninoculated control. Enhanced yield of inoculated plants grown under high CO_2 concentrations were observed.
- A two-year greenhouse study aimed to quantify changes in physical and thermal soil properties, and evapotranspiration (ET) rate of pecan (Carya illinoinensis (Wangenh.) K. Koch) irrigated with BGW and RO concentrate. Pecan irrigated with RO concentrate had the lowest ET among irrigation treatments. Soil thermal conductivities and soil water contents in BGW and RO irrigated pots were higher than control. A new four parameters-based model using EC and VWC explained 96% of variability of K (average $R^2 = 0.96$, RMSE = 0.096, NRMSE=11.14%). The sensitivity analysis showed that the contribution of VWC to K was greater than that of EC
- Irrigation with RO concentrate and brackish groundwater impacts pecan tree growth and physiology (Ben Ali A., M.K. Shukla, B. Schutte, and C. Gard): Water scarcity has become a salient problem in southern New Mexico. A combination of drought and a decrease in surface water for irrigation encouraged to search for other sources of water. Desalination of brackish groundwater (BGW) using reverse osmosis (RO) results in a highly salty water or RO concentrate. In this study, impacts of using BGW and RO concentrate for irrigating pecan trees inside a greenhouse were evaluated. The objective was to determine if pecan trees are suitable for irrigation with BGW and RO concentrate, and evaluate the possible effects on pecan growth and physiological parameters. For each of two growing seasons (2017 and 2018), continuous irrigation with RO concentrate to pecan cannot be made, and new irrigation scheduling protocols based on salinity tolerance will be needed.

Public service**:**

- Editor-Book Review, Vadose Zone Journal
- Technical editor, Soil Physics and Hydrology, Soil Science Society of America Journal
- Editor in Chief Soil Health Journal
- International Arid Lands Consortium initiatives (IALC) Executive Board Member
- Member Globalization/ Internationalization Committee of NMSU (2020-Present)

- Member sub-group- Mexico Strategy of NMSU (2020- Present)
- Member Association of Public Land Grant Universities

Consulting:

- Water use efficiency Ndrip System
- Soil and Water Analysis Interpretations, Zeigler Geologic Consulting LLC. (2019 - Present).
- Soil moisture sensor testing, Meter Group. (2018 - Present).
- Visiting Professor China Agricultural University

Funding:

- Shukla M.K. (PI; lead Education), S Norris, UC Davis (Lead), U of A, and Fresno. 2021 Sustainability of Groundwater and Irrigated Agriculture in the Western United States under a Changing Climate. USDA/AFRI. 10M.
- Shukla M.K. (PI), R. Ghimire (Co-PI). 2021. Can we increase soil organic C sequestration by efficient rangeland management? NGL, Energy Partners LP, ($132K)
- Shukla M.K. (PI).2021. Lower Rio Grande Land Management Practices for Uncultivated Agricultural Fields. NMDA and ISC ($135K)

<u>Texas A&M University (Briana Wyatt)</u>

- Novel cosmic ray neutron sensor accurately captures field-scale soil moisture trends under heterogeneous soil textures. *Kade Flynn, Briana Wyatt, and Kevin McInnes.* Soil moisture is a critical variable influencing plant water uptake, rainfall-runoff partitioning, and near-surface atmospheric conditions. Soil moisture measurements are typically made using either in-situ sensors or by collecting samples, both methods which have a small spatial footprint or, in recent years, by remote sensing satellites with large spatial footprints. The cosmic ray neutron sensor (CRNS) is a proximal technology which provides estimates of field-averaged soil moisture within a radius of up to 240 m from the sensor, offering a much larger sensing footprint than point measurements and providing field-scale information that satellite soil moisture observations cannot capture. Here we compare volumetric soil moisture estimates derived from a novel, less expensive lithium (Li) foil-based CRNS to those from a more expensive commercially available 3He-based CRNS, to measurements from in-situ sensors, and to four intensive surveys of soil moisture in a field with highly variable soil texture. Our results indicate that the accuracy of the Li foil CRNS is comparable to that of the commercially available sensors (MAD = 0.020 m3 m−3), as are the detection radius and depth. Additionally, both sensors capture the influence of soil textural variability on field-average soil moisture. Because novel Li foil-based CRNSs are comparable in accuracy to and much less expensive than current commercially available CRNSs, there is strong potential for future adoption by land and water managers and increased adoption by researchers interested in obtaining field-scale estimates of soil moisture to improve water conservation and sustainability.

- Improving Seasonal Streamflow Forecasts for Surface Water Irrigation Districts By Incorporating Soil Moisture Information Derived from Remote Sensing. *Briana Wyatt, Mingxiu Wang, and Tyson Ochsner.* Surface water managers in the Great Plains face major challenges due to the region's drought-prone climate and large inter-annual

variability in rainfall and streamflow, and they do not have access to seasonal streamflow forecasts like those widely-used in the snow-dominated watersheds of the western US. Recently completed work by the PIs shows that in-situ soil moisture measurements can be used to produce accurate streamflow forecasts in rainfall-dominated regions and are able to provide >50% improvement over streamflow forecasts based on antecedent precipitation alone. However, the use of this method is currently restricted to watersheds where data from in-situ soil moisture monitoring stations are readily available. The goal of the current research is to determine whether utilizing remotely-sensed soil moisture data will allow the creation of similarly effective seasonal streamflow forecasts in areas lacking in-situ soil moisture monitoring networks. Preliminary results indicate that remote sensing-based forecasts including soil moisture information are improved over precipitation-only forecasts in some watersheds but not in others.

University of Wyoming (Thijs Kelleners)

- Maintained a soil moisture & rainfall measurement network of 17 sites in rangelands across Wyoming
- Disassembled Electrical Resistivity Tomography sites in Reynolds Creek, Idaho, Jemez River Basin, New Mexico, and the Bighorn Mountains, Wyoming after several years of continuous monitoring.
- Maintained other Electrical Resistivity Tomography sites in Reynolds Creek, Idaho, Upper Sheep Creek, Idaho, and Snowy Range, Wyoming.
- Maintained snow and soil moisture monitoring equipment in the Laramie Range, Wyoming and the Snowy Range, Wyoming

University of California-Riverside (Jirka Šimůnek)

In 2021, we organized four short courses on using HYDRUS models. The first one was mainly for participants from the US and Canada, the second one mainly for attendees from India, the third one main for participants from Europe, and finally, the fourth one was mainly for the East Asian countries and Australia. Over 200 students participated in these short courses.

Meetings attended:

- W-4188 Western Regional Soil Physics Group Meeting, Online, January 7, 2021.
- ISMC (International Soil Modelling Consortium) meeting, online, May 18-22, 2021.
- W-4188 Western Regional Soil Physics Group Meeting, Online, May 27, 2021.
- Annual Meeting of Soil Science Society of America, Salt Lake City, Utah, November 7-10, 2021.
- W-4128 Western Regional Soil Physics Group Meeting (Microirrigation: A sustainable technology for crop intensification and improved water productivity), online, December 2, 2021.
- Fall Meeting of American Geophysical Union, New Orleans, Louisiana, December 13-17. 2021.

HYDRUS Teaching:

- An online short course “Modeling of water flow and contaminant transport in porous media using the HYDRUS software packages” organized by PC Progress, Prague, Czech

Republic, online, March 16–17, 2021. Sole instructor (72 participants, mostly from the US and Canada).

- An online "HYDRUS Model Workshop" organized by Society of Young Agriculture and Hydrology Scholars of India (SYAHI) and PC Progress, August 20, 2021. Another instructor: Pankaj K. Gupta (108 participants from 21 countries, mostly from India and Middle East).
- An online short course "Advanced modeling of water flow and contaminant transport in porous media using the HYDRUS software packages" organized by Czech University of Life Sciences, Prague, Faculty of Agrobiology, Food and Natural Resource, Prague, Czech Republic, August 31–September 2, 2021. Another instructor: M. Th. van Genuchten (38 participants, mostly from the EU countries).
- An online short course "Advanced modeling of water flow and contaminant transport in porous media using the HYDRUS software packages" organized by PC Progress, Prague, Czech Republic, online, September 14–16, 2021. Sole instructor (27 participants, mostly Asia and Australia, also some from USA).

Public service:

- Editor-in-Chief, Journal of Hydrology
- Associate editor, Journal of Hydrology and Hydromechanics

Invited Presentations:

- Numerical Modeling of Vadose Zone Processes using HYDRUS and its Specialized Modules. The Leo Walsh Distinguished Lecture in Soil Science, University of Wisconsin, Madison, April 28, 2021.
- Modelling Soil Physical Processes for improving resource use efficiency in agriculture. Organized by Indian Society of Agro-Physics" in association with Division of Agricultural Physics, ICAR - Indian Agriculture Research Institute, December 8, 2021 (online).

Awards:

- 2021 Hydrological Sciences Award (Established in 1956 and granted by the Hydrology Section of the American Geophysical Union for outstanding contributions to the Science of Hydrology over a career, with an emphasis on the past five years. It is the highest disciplinary recognition for senior scientists within the Hydrology section.)

<u>USDA-ARS, Bushland, Texas (Schwartz and Evett)</u>

- We continued work with a Cooperative Research and Development Agreement partner to improve new, low-cost soil water and bulk electrical conductivity sensors based on miniaturized TDR circuitry that is directly coupled to the probe waveguide. The work also included field testing of new sensors (TDR-315N and TDR-310N) at Beltsville, Maryland; Bushland, Texas; and Amman, Jordan. Work continued on a Cooperative Research and Development Agreement with Acclima, Inc. initiated in 2019 to utilize acquired waveforms from the TDR-315H sensor for the characterization of soil properties and to improve water content calibrations specific to a given soil. Acclima introduced the new TDR-315N and TDR-310N sensors based in part on results of this work.

- We continued CRADA cooperation with ARS Beltsville and Acclima, Inc. in their development of a low-cost, low-power node and gateway system to gather data from SDI-12 based sensors and transmit it wirelessly from nodes to a gateway at field's edge using the LoRa radio transmission protocol, and from gateway to the internet using the cellular telephone network. At the moment, Hologram is the Internet service provider for data upload and storage. The CRADA with Acclima, Inc. resulted in a completely redesigned commercial system that was deployed nationally and in five locations internationally. Beta test results guided improvements and refinements of the hardware and firmware and led to development of new capabilities, including a "Receiver" mode that allows the gateway to continue operation as a master datalogger in cases where a SIM is stolen or cellular service is unavailable, and ability of the nodes to acquire data via SDI-12 from more sensors (e.g., the Apogee IRT, and the METER ATMOS weather station). Two journal articles described results to date (Evett et al., 2021; Thompson et al., 2021).
- Collaboration with the Centro Regional de Estudios de Agua (CREA) University of Castilla-La Mancha, Albacete, Spain was continued to adapt and improve irrigation scheduling strategies that involve some degree of planned or unplanned water stress. A calibrated maize yield model was combined with climatic scenarios and an algorithm to spatially and temporally allocate water under a center pivot with limited irrigation capacities. This approach was utilized to determine the irrigated fraction that optimized yield and net economic returns. Because greater irrigation volume did not always increase net returns, there is an opportunity to both increase profitability and conserve water by irrigating a fraction of the area.
- We continued development of sensors, sensing systems, software and hardware systems and systems integration for scheduling and control of variable rate irrigation systems. This involved laboratory prototyping, testing and calibration, and field testing of system components and the entire Irrigation Scheduling Supervisory Control and Data Acquisition (ISSCADA) system on two center pivots at Bushland, Texas; and one center pivot at each of Florence, South Carolina; Portageville, Missouri; and Stoneville, Mississippi. Test results indicated yields and water use efficiency at least as good as those obtained using alternative and more labor-intensive scientific irrigation scheduling methods based on soil water sensing alone and considerably better than county wide yields and water use efficiencies. This work resulted in several presentations at the delayed 6th Decennial Irrigation Symposium in December 2021 (Andrade et al., 2021a,b; Evett et al. 2021a,b; Marek et al., 2021; O'Shaughnessy et al, 2021; Stone et al., 2021; Sui et al., 2021; Vories et al., 2021). Our collaboration with University of Nebraska continued to field test the system in comparison with other irrigation management protocols in Nebraska.
- We continued long-term work comparing evapotranspiration (ET) by field soil water balance to ET by weighing lysimeter, contrasting sprinkler irrigation with subsurface drip irrigation (SDI). The 2021 cotton crop was successfully grown and harvested. This included work on characterizing the energy and water balances of irrigated cropping systems using weighing lysimeters, soil water sensors, and a host of radiative, sensible and latent heat flux sensing systems. This work resulted in journal articles on crop coefficients for soybean (Marek et al., 2021a), on maize water productivity effects of irrigation management alternatives (Marek et al., 2021b), on the economics of adopting

different irrigation application methods (Fan et al., 2021), and on instrumentation issues affecting eddy covariances sensing systems (Kutikoff et al., 2021).

- We continued sharing of comprehensive 15-minute quality-controlled microclimate, plant growth, energy and water balance, and soil water content data with Agricultural Model Intercomparison and Improvement Project (AgMIP) maize (2013 and 2016 years) and winter wheat (1989-1990, 1991-1992, and 1992-1993 seasons) modeling teams. A meeting presentation described preliminary results of the maize modeling teamwork (Kimball et al., 2021).
- We finalized work on assessment of climate change effects on watershed soil and water status and dynamics with participants in the IAEA Coordinated Research Project (CRP) D1.50.17 on "Nuclear Techniques for a Better Understanding of the Impact of Climate Change on Soil Erosion in Upland Agro-ecosystems".
- We continued work with ICARDA, USFS, the Jordanian National Centre for Agricultural Research, and an NGO (WADI) in Jordan, including training on sensor and node and gateway telemetry systems at three watersheds and a weighing lysimeter in Jordan, and a new system deployed by ICARDA in Lebanon. This included ongoing work on the ICARDA Water & Livelihoods Initiative watershed outside Amman, Jordan, at the Royal Botanical Gardens in Jordan, at the Deir Alla Research Station large weighing lysimeter in the Jordan Valley, and at a new watershed site in the Badia of northern Jordan.
- We continued work with University partners (TTU, TAMU) to evaluate seasonal and depth dependent soil water use patterns, fiber yield and quality, WUE, to water stress levels in cotton varieties with diverse morphological expressions under SDI.
- We continued evaluation of three profiles of TDR soil water sensors in a precision weighing lysimeter to assess to what degree the sensor profile data could be used to accurately assess evapotranspiration. Preliminary results presented at the 2021 AGU meeting indicated that the deep, dense profiles of TDR sensors were successful in accurately determining soil profile water change in storage (https://doi.org/10.1002/essoar.10508596.1).
- We continued work with Texas A&M AgriLife Research on field testing of the Campbell Scientific SoilVue soil water sensing system with six installations, two each, respectively, in corn fields irrigated at 50%, 75% and 100% of full irrigation to meet crop ET requirements. SoilVue sensors were installed 30 cm from neutron probe access tubes, and TDR-315L and TDR-315H sensors were installed between the access tube and SoilVue sensors at the center depths of SoilVue sensors.

Presentations and Meetings (invited):

- Evett, S.R. 2021. ET by Soil Water Balance: Weighing lysimetry and soil water sensing approaches. Presented to the ICARDA/FAO Webinar Series on ET Measurement, October 13, 2021.
- Evett, S.R. 2021. The MERIMIS project – Palestine-Jordan-Israel-USA Irrigation Management Information System. Presented to the hybrid virtual conference "Achieving Sustainable Agriculture in Arid Regions", May 24 and 26, 2021. Agricultural Research Organization, Israel.
- Evett, S.R. 2021. Environmental Monitoring with a Node & Gateway System in Extreme Weather – Texas. Presented to the Precision Sustainable Agriculture (PSA) Modeling Team, August 31, 2021.

- Evett, S.R., O'Shaughnessy, S.A., Colaizzi, P.D., Schwartz, R.C. Irrigation Technology Management and Scheduling. Webinar presented to the Irrigation Association, March 18, 2021.
- Evett, S.R. 2021. The State of Soil Water Monitoring. Keynote presentation to the National Soil Moisture Workshop, August 18-19, 2021.
- Evett, S.R., et al. 2021a. Theory and development of a VRI decision support system: The USDA-ARS ISSCADA approach. 6th Decennial National Irrigation Symposium, 6-8, December 2021, San Diego, California USA
- Evett, S.R., O'Shaughnessy, S.A., Andrade, M.A., Colaizzi, P.D., Schwartz, R.C. 2021. Theory and development of a variable rate irrigation system. INOVAGRI Meeting Virtual 2021, and XXX CONRID (National Congress of Irrigation and Drainage), Brazil.
- Schomberg, H., Thompson, A., Evett S. Networked System for On-farm Soil Water Measurements. Presented to the Soil Moisture Working Group, February 3, 2021.
- Schwartz, R.C. Gestión de Riego I. Determinación de las necesidades de riego de los cultivos. Escuela Polytecnica Superior de Agricultura de Manabi (EPSAM), Dept. Agricultural Engineering Faculty/Students (Virtual). Feburary 3, 2021.
- Schwartz, R.C. Water allocation strategies and tools for irrigation management decisions. College of Agriculture and Health Sciences Research Seminar Series, Prairie View A&M University (Virtual). April 1, 2021.

Presentations and Meetings (volunteered):

- Andrade, M.A., et al. 2021a. ARSPIVOT, a sensor-based decision support software for variable-rate irrigation center pivot systems: Part A. Development. 6th Decennial National Irrigation Symposium, 6-8, December 2021, San Diego, California USA
- Andrade, M.A., et al. 2021b. ARSPIVOT, a sensor-based decision support software for variable-rate irrigation center pivot systems: Part B. Application. 6th Decennial National Irrigation Symposium, 6-8, December 2021, San Diego, California USA
- Evett, S.R., Schwartz, R.C., Strohmeier, S. Haddad, M., Schomberg, H., Thompson, A. 2021. Agro-ecosystem data in the Cloud – Utility of a node and gateway system. Presented to the Final Research Coordination Meeting of the International Atomic Energy Agency CRP D1.50.17, July 5-9, 2021, Vienna, Austria (virtual meeting)
- Evett, S.R., Thompson, A., Schomberg, H. 2021. Environmental Monitoring with A Node & Gateway System in Extreme Weather. Presented to the W4188 Research Committee Technical Meeting, May 27, 2021.
- Evett, S.R., et al. 2021b. Are crop coefficients for SDI different from those for sprinkler irrigation application? 6th Decennial National Irrigation Symposium, 6-8, December 2021, San Diego, California USA
- Evett, S.R., Marek, G.W., Schwartz, R.C., Colaizzi, P.D., Brauer, D.K. 2021c. Can TDR Soil Water Sensors Determine Change in Storage as Well as a Weighing Lysimeter or Neutron Probe? Presented to the W4128 Microirrigation Research Committee Meeting, December 2, 2021.
- Evett, S. R., G. Marek, R. Schwartz, P. Colaizzi, and D. Brauer. 2021. Can Dense, Deep Profiles of Soil Water Sensors Determine Change in Storage as Well as a Weighing Lysimeter or Neutron Probe? Presented to the AGU 2021 Fall Meeting, session H55N, "Evapotranspiration (ET) - Advances in In Situ ET Measurements and Remote Sensing-

Based ET Estimation, Mapping, and Evaluation", 13-17 December 2021, as presentation H55N-0887. https://doi.org/10.1002/essoar.10508596.1

- Marek, G.W., et al. 2021. Comparison of lysimeter-derived crop coefficients for legacy and modern drought-tolerant maize hybrids in the Texas High Plains. 6th Decennial National Irrigation Symposium, 6-8, December 2021, San Diego, California USA
- O'Shaughnessy, S.A., et al. 2021. Irrigation management of potatoes using sensor feedback: Texas High Plains. 6th Decennial National Irrigation Symposium, 6-8, December 2021, San Diego, California USA
- Stone, K.C., et al. 2021. A variable-rate irrigation decision support system for corn in the U.S. Eastern Coastal Plain. 6th Decennial National Irrigation Symposium, 6-8, December 2021, San Diego, California USA
- Sui, R., et al. 2021. Evaluation of a decision support system for variable-rate irrigation in a humid region. 6th Decennial National Irrigation Symposium, 6-8, December 2021, San Diego, California USA
- Vories, E.D., et. al. 2021. Advances in precision irrigation management of cotton. 6th Decennial National Irrigation Symposium, 6-8, December 2021, San Diego, California USA

Virginia Tech (Ryan Stewart)

- We tested different compounds to reduce soil water content and infiltration in vineyard soils as a way to better manage fruit quality.
- We verified the performance of a new instrument for passively collecting flow-weighted water samples during surface runoff measurements.
- We performed experiments to understand nitrogen cycling in soilless substrates used in nursery production.
- We analyzed soil carbon dioxide and water content measurements to understand carbon dioxide diffusion processes in a karst hillslope.
- We performed field measurements using geophysics (e.g., electrical resistivity tomography) to better understand preferential flow processes.
- We attended the following meetings and workshops:
    - Virginia Vineyards Association Winter Technical Meeting (Virtual). February 25-26, 2021.
    - EGU General Assembly (Virtual), April 19-30, 2021.
    - W4188 Annual Meeting (Virtual), May 27, 2021.
    - 9th World Conference on Ecological Restoration (Virtual). June 21-24, 2021.
    - American Society for Enology & Viticulture National Conference (Virtual). June 21-24, 2021
    - American Society for Enology & Viticulture Eastern Section Conference (Virtual). July 7-8, 2021.
    - American Society for Horticultural Science (ASHS) Annual Meeting. Denver, CO. August 5-9, 2021.
    - Virginia Association of Professional Soil Scientists (VAPSS) 2021 Annual Fall Conference (Virtual). September 23, 2021.
    - ASA, CSSA, SSSA International Annual Meeting. Salt Lake City, Utah, November 7-10, 2021.

Oklahoma State University (Tyson Ochsner)

- Continued research to determine the potential for applying soil moisture-informed streamflow forecasting methods using soil moisture estimates from satellite remote sensing.
- Developed forecasts for cooperating surface water irrigation districts in three states who could use the forecasts for planning water allocations.

Kansas State University (Andres Patrignani)

- Deployed hydrological monitoring network at the Konza Prairie to study the connection between rootzone soil moisture and streamflow in tallgrass prairies.
- Continue with research on a biodegradable polymer to reduce evaporative losses
- Continue work on prototyping a deep neural network to quantify bare soil, green canopy cover, and crop residue using digital images.
- Continue collecting soil samples at new monitoring stations of the Kansas Mesonet.

Milestones

***Objective 1*:** To improve our fundamental understanding of vadose zone physical properties and processes, and how they interact with other environmental and biogeochemical processes across various spatial and temporal scales.

U.S. Salinity Laboratory (Todd Skaggs and Ray Anderson)

- **New release of the Rosetta model for estimating soil hydraulic parameters**. Rosetta is a widely used machine learning model that predicts soil hydraulic parameters from more readily available soil characterization data. ARS scientists in Riverside, California, released a new implementation of Rosetta called "rosetta-soil". The new implementation can be accessed (i.) as a web browser application (https://www.handbook60.org/rosetta), (ii.) via a representational state transfer application programming interface (REST API), or (iii.) as a stand-alone Python application (https://github.com/usda-ars-ussl/rosettasoil). rosetta-soil" provides a valuable new set of tools for researchers and engineers who require rapid estimates of soil hydraulic properties

University of California Riverside (Hoori Ajami)

- Improve mechanistic understanding of groundwater recovery to droughts.
- Improve groundwater recharge estimation from mountain catchments by integrating hydrological and hydrochemical models.

Texas Tech University (Sanjit K. Deb)

- Surface soil water content (SWC) is a major determinant of crop production, and accurately
  retrieving SWC plays a crucial role in effective water management. Unmanned aerial systems
  (UAS) can acquire images with high temporal and spatial resolutions for SWC monitoring at the field scale. Gu et al. (2021) developed and evaluated an algorithm to

retrieve SWC by integrating soil texture into a vegetation index derived from UAS multispectral and thermal images. Soil texture was incorporated into the trapezoid model based on the relationship between soil texture and the lower and upper limits of SWC to form the texture temperature vegetation dryness index (TTVDI). The application of the TTVDI model based on high-resolution multispectral and thermal UAS images showed the potential to accurately and timely retrieve SWC at the field scale.

- Use of waste products from other components of the animal production chain, such as applying composted manure from feedlot operations to grazed pastures, may provide an additional means of improving soil health and sustainability of semiarid perennial pasture systems for livestock production. Otuya et al. (2021) examined the impact of composted animal manure on microbial communities and soil carbon in semi-arid improved pasture (i.e., grass-only versus grass-alfalfa mix) systems to provide an additional means of improving soil health and sustainability of perennial pasture systems for livestock production in the Texas Southern High Plains.
- Increased water scarcity necessitates the implementation of water-conserving plant- and soil-based irrigation management practices to sustain crop production, especially in water-limited areas. Parkash et al. (2021a; 2021b) evaluated the effects of deficit irrigation levels and cultivars on root distribution pattern, soil water depletion, water use efficiency, and yield and quality of vegetable crop (e.g., cucumber).
- Turfgrass systems have been identified as potential sources of nitrate leaching and subsequent groundwater contamination. Geza et al. (2021) modeled and quantified nitrate leaching from bermudagrass and buffalograss established by either seed or sod and irrigated with either tailored (defined as reclaimed water with an N concentration of 15 mg L^{-1}) or potable water and fertilized with calcium nitrate. Soil texture was even more important than nitrate application rate in predicting nitrate leaching losses and the HYDRUS (2D/3D) simulation demonstrated that nitrate leaching was affected more by denitrification than by plant uptake.
- Perfluoro alkyl acids (PFAAs) are known to bioconcentrate in plants grown in contaminated soils; the potential risk from consuming these plants is currently less understood. Using a combination of experiment/research and literature data on plant uptake of PFAAs from soil, Lasee et al. (2021) developed equations for predicting PFAA bioconcentration factors (BCFs) for plant shoot and root tissues grown in soils with a known percentage of organic carbon. The calculated BCFs were then applied to various scenarios with measured soil PFAA concentrations to estimate PFAA concentrations in plants and potential exposure to humans and animals consuming harvested vegetation.

<u>New Mexico State University (Kenneth Carroll)</u>

- Characterization and description of physical properties of the vadose zone
    - Rucker et al. (2021) mapped the subsurface contact between soil and limestone bedrock in Oakridge, TN, using noninvasive characterization combining electrical resistivity and induced polarization geophysics, which included comparison of multiple interface picking methods. This method was used to locate buried channel deposits.
- Transport and transformations of solutes, nanoparticles, and emerging contaminants
    - Huang et al. (2021) investigated the co-transport behavior of per- and polyfluoroalkyl substances (PFAS) and hexavalent chromium (Cr(VI)) in porous

media. The sorption retardation of PFOS was decreased in the presence of Cr(VI), but the transport and retardation of PFOA was not affected by the presence of Cr(VI). The reduction of PFOS retardation caused by Cr(VI) is likely due to sorption competition for both organic carbon and inorganic (metal-oxides and clay minerals) domains. The results of this study indicate that the presence of Cr(VI) has the potential to significantly increase the migration potential of PFOS in soil and groundwater.

- Akyol et al. (2021) compared sorption and solute transport of atrazine, 2,4-dichlorophenoxyacetic acid (2,4-D), glyphosate, and metribuzine in an alkaline agricultural soil, and found 2,4-D and metribuzine sorption amount was low and comparable, whereas increased sorption Kd was observed for atrazine and glyphosate, which was attributed to partitioning into soil organic matter.
- Wang et al. (2021) evaluated transport of PFOS in aquifer sediment comprising different geochemical properties, and to compare the behavior to that observed for PFOS transport in soil and sand. PFOS has more extensive tailing in the soil compared to the sand indicating sorption to multiple solid-surface sites. A three-component distributed-sorption model was developed that accounted for contributions from soil organic carbon, metal oxides, and silt+clay fraction.

University of California-Davis (Majdi Abou Najm)

- Conduct critical review on infiltration:
  - Completed review on 1D and 3D problems
  - Completed review on empirical models
  - Summarized the modeling frameworks of those 70 models
  - Generated first draft of manuscript with plan to complete additional components (including adding shrink-swell soils and other special cases) and submit in 2022.

- Conduct systematic review on soil structure and its impact on infiltration:
  - Collected review data on around 800 unique plots
  - Conducted statistical analysis and regressions on data
  - Summarized the results and developed pedotransfer functions
  - Generated first draft of manuscript with plan to complete additional components and submit in 2022.

University of Wisconsin-Madison (Jingyi Huang)

- Models were developed for predicting future surface soil moisture dynamics across the globe and continental USA
- New vis-NIR spectral models developed for rapid estimating soil water retention curves

Texas A&M University (Binayak P. Mohanty)

- Sehgal et al (2021a) developed global surface soil moisture drydown patterns using SMAP satellite soil soil moisture data. Seasonally variable soil, vegetative, and atmospheric controls are observed in effective soil water retention parameters at satellite footprint scale across the globe.
- Jena, et al. (2021a) developed a generalizable Pedo-Transfer Function for saturated hydraulic conductivity using transfer learning and predictor selector algorithm. This

design makes Ks estimation accurate, transferrable, and cost-effective.

- Jena, et al (2021b) developed a prediction framework for groundwater variability using hydrological, geological, and climatological controls in Odisha, India. The framework provides a hybrid tool for water availability in data-sparse regions.
- Singh, et al (2021) developed a high-Resolution soil moisture retrieval using SMAP L-band radiometer and RISAT-1 C-band Radar data in the paddy dominated tropical region of India. The findings will help new active-passive soil moisture retrieval algorithms in challenging geophysical conditions (i.e., dynamic surface water bodies).
- Jacot et al (2021) used PhenoCam measurements and image analysis to inform the ALMANAC process-based simulation model. The results show how PhenoCam data can make a valuable contribution to validate process-based models.

North Carolina State University (Josh Heitman) and Iowa State University (Robert Horton)

- We developed an approach to estimate the Van Genuchten model parameters from electrical conductivity and water content measurements and other easily attainable soil properties. Data of five soils obtained from the lab measurements and literature show that the proposed method performed well when compared to direct soil water retention curves (SWRC) measurements (with an average RMSE and an average bias of 0.041 cm3 cm-3 and 0.008 cm3 cm-3, respectively). Results indicated that the electrical conductivity-based method accurately estimated SWRCs.
- Based on the similarities between a soil water retention curve (SWRC) and a soil thermal conductivity (λ) versus water content (θ) curve, we developed a way to estimate the Van Genuchten model shape parameter from the $\lambda(\theta)$ model shape parameter based on a model calibration with datasets obtained from 10 soils. The other parameters were estimated from selected soil properties. Another six soils were used to validate and the model results indicated that the proposed method accurately estimated SWRC curves from $\lambda(\theta)$ curves and selected soil properties.
- We developed a process-based simulation model for surface water and heat transfer with two main ambient factors, residue mulch and surface runoff. Surface water content and temperature were simulated with a modified Philip and de Vries (1957) model, including precipitation interception and radiation attenuation in residue mulch. Surface runoff was modeled with the Saint-Venant equation. Residue decomposition, as a derivative, was computed via a modified CERES-N model. Interactions between surface runoff and residue mulch, and dynamic decreases in residue mulch thickness due to decomposition were also included. The model was modularized and deployed with a "layered module architecture" in MAIZSIM, such that the main ambient factors, interactions, and derivatives can be activated or deactivated based on scenarios or user settings. The study demonstrated that residue mulch conserved soil water and reduced temporal variations of surface temperature and the feasibility of synthesizing multiple factors via a modularized model architecture.

University of Delaware (Yan Jin)

- Gained improved understanding on mechanisms of water retention mediated by rhizobacteria.
- Contributed to databases of water retention function, saturated and unsaturated hydraulic conductivities for salt-affected and SOC-rich coastal soils.

- Used the above data to evaluated several commonly used PTFs for estimation of soil hydraulic conductivity functions.
- Developed a new method coupling oxygen optode and zamography to determine how hydraulic redistribution affects soil organic matter mineralization. Our findings provide new insights on how plants self-regulate rhizosphere water dynamics for nutrient availability.
- Gained understanding on how colloid-facilitated transport affects stream water chemistry through metadata analysis of long-term monitoring results from a catchment. Our analysis revealed a potential role that colloidal Fe and Al oxyhydroxides play in organic carbon fate and transport.

University of Kentucky (Ole Wendroth)

- Soil water balance component observations for quantifying daily soil water storage change, seepage and profile drainage water quality.
- Spatial variability of profile soil water dynamics, plant water uptake and suitable irrigation rate.

North Dakota State University (Aaron Daigh)

- We were able to quantify a range of landslide conditioning factors across North Dakota. Of the 24,123 identified landslides, nearly 97% of those occurs in vadose zones with generally low pore water salinity and sodium adsorption ratios (SAR; i.e., <5.0 dS/m and <7.0 SAR, with maximum frequency occurring at 1.5 dS/m and 0.5 SAR) even though high pore water salinity and SAR is characteristic of many soils across the state.

Washington State University (Markus Flury)

- Biochar is being used as a soil amendment to improve soil hydraulic properties. It has been reported that biochar increases plant-available water, particularly in coarse-textured soils; however, effects on fine-textured soils are less pronounced. We quantified the effects of biochar particle size on plant-available water in sand, silt loam, and clay soils. Our results show that biochar amendments increased the plant-available water (when expressed gravimetrically) of all three soils, particularly at the highest biochar application rate. Although the absolute increase in plant-available water was largest for the silt loam soil, the relative increase of plant-available water was greater for the sand than for the silt loam and clay. Our results show that biochar is a beneficial soil amendment to increase water holding capacity for soils.

The University of Arizona (Markus Tuller)

- Developed new technique for rapid estimation of soil hydraulic properties based on shortwave infrared imaging and inverse numerical modeling for rapid estimation of soil hydraulic properties.
- Developed new method to estimate water repellency of soils with high organic carbon contents from water vapor sorption isotherms.
- Developed new method to estimate Atterberg limits of soils with high organic carbon contents from hygroscopic water content.
- Developed new analytical model to determine the information depth of NIR/SWIR soil reflectance spectroscopy

New Mexico State University (Manoj Shukla)

- Proposed a new reduction function o predict tomato yield and ET responses to salinity.
- Modified SWAP model for soil water and heat dynamics under film mulching conditions.

University of Idaho (Robert Heinse)

- Demonstrated that terracette landforms can be mapped automatically and with computational efficiency using fft on very-high resolution imagery.

University of Wyoming (Thijs Kelleners)

- Quantification of subsurface architecture for six hillslopes with different geologies (intrusive igneous rock, volcanic materials, and glacial deposits) by combining electrical resistivity and seismic refraction data

University of California-Riverside (Jirka Šimůnek)

We continue to expand the capabilities of the HYDRUS modeling environment by developing specialized modules for more complex applications that cannot be solved using its standard versions. The standard versions of HYDRUS, as well as its specialized modules, have been used by myself, my students, and my collaborators in multiple applications described below.

Hydrological Applications

- Sasidharan et al. (2021) carried out numerical simulations using HYDRUS (2D/3D) to evaluate and compare recharge from drywells and infiltration basins.
- Liu et al. (2021) compared different ensemble data assimilation methods for the estimation of time-varying soil hydraulic parameters.
- Zheng et al. (2021) developed the freezing/thawing module for Hydrus-1D and applied it at multiple locations in Chine to simulate the coupled movement of water, vapor, and heat.
- Kacimov et al. (2021) revisited the concept of Girinskii's potential to evaluate water table rise in urban shallow aquifer with vertically-heterogeneous soils.
- Kacimov et al. (2021) developed an analytical travelling-wave solutions for wet wedges propagating into dry soils and used HYDRUS to verify these analytical solutions.
- Kacimov et al. (2021) evaluated seepage from topographic depressions on Earth and Mars using newly developed analytical solutions and HYDRUS modeling.
- Sharma et al. (2021) developed a semi-analytical solution for non-equilibrium solute transport in dual-permeability porous media and used HYDRUS to verify these analytical solutions.
- Zhou et al. (2021) adapted HYDRUS-1D to simulate the transport of soil water isotopes with evaporation fractionation. We also implemented a particle tracking algorithm to be able to simulate water age at different depth and in different hydrological fluxes (e.g., root water uptake and recharge).
- Nasta et al. (2021) assessed the nitrate vulnerability of shallow aquifers under Mediterranean climate conditions using HYDRUS-1D.
- Brunetti et al. (2021) carried out an experimental and numerical analysis of nitrogen turnover in a shallow aquifer.

- Gumuła-Kawęcka et al. (2021) estimated groundwater recharge on the Brda outwash plain in northern Poland using unsaturated zone modeling, a water table fluctuation method, and tracer experiments.
- Vanda et al. (2021) used a graph-based conflict resolution framework that considered spatial-temporal-quantitative uncertainties to evaluate reservoir operations under accidental MTBE pollution.
- Jaiswal et al. (2021) used parasite inversion of Parlange's three-parameter infiltration equation to determine the hydraulic properties and time-validity of Philip's two-term infiltration equation for 12 different textural classes.

Virginia Tech (Ryan Stewart)

- Completed a study to assess magnitude, direction, and controls on carbon dioxide fluxes in a pasture-covered karst area.

Objective 2: Develop and test new instrumentation, methods and models to improve the mechanistic understanding of soil processes and the quality of soil information and knowledge.

U.S. Salinity Laboratory (Todd Skaggs and Ray Anderson)

- Almonds have higher salinity tolerance than previously believed. Almonds are a major crop in California, contributing over $9 billion/year to the state's economy, and consuming a significant amount of water. However, almonds have been viewed as a salt-sensitive crop. This salt sensitivity presents a major irrigation challenge for California growers (especially in the Western San Joaquin Valley) who may need to irrigate with higher salinity groundwater during drought periods when lower salinity surface water is unavailable. ARS researchers at Riverside, California, evaluated the impact of irrigating with lower quality groundwater via a comparison study with less saline orchards with better groundwater. They found that current, commercial, almond salinity tolerance was significantly higher than previously reported. This discovery provides a tool for growers to temporarily use higher salinity groundwater temporarily to mitigate the lack of surface water during a drought and provides additional potential for increased and sustainable almond production in the Western San Joaquin Valley.

- New satellite algorithm provides improved evapotranspiration for crop water use and irrigation management. Recent droughts in the western United States have put tremendous strain on water resources, and there is increased pressure on the agricultural community to improve irrigation efficiency. However, established satellite evapotranspiration (ET) algorithms (and particularly thermal algorithms that work well in the western United States) have higher latency and longer revisit times that limit their utility for managing irrigation in specialty vegetable crops. ARS researchers at Riverside, California, and Maricopa, Arizona, have evaluated a new thermal satellite ET algorithm based on the international space station (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station – ECOSTRESS) that overflies farms once every four days (instead of ~16 days for the Landsat satellite). They found that ECOSTRESS works very

well for measuring crop water use in the western United States. This discovery provides another tool that could be adapted to help farmers improve irrigation scheduling.

Desert Research Institute (Markus Berli)

- Model evaluation for water infiltration into hydrophobic soil
- Improved model to simulate water infiltration, redistribution and evaporation for arid soils

University of California-Riverside (Amir Haghverdi)

- We conducted a comprehensive regional geospatial analysis to determine percentages of variable fields, variability explained by zoning and temporal stability of MZs in the southern California agriculture region.

University of California-Riverside (Hoori Ajami)

- Improve vegetation parameterization in land surface models
- Improve methodologies for quantifying uncertainty in hydrologic models

New Mexico State University (Kenneth Carroll)

- Quantifying near-surface processes with instruments and analyses
    - Mohamed et al. (2021a) compared fiber-optic distributed temperature sensing (FO-DTS) and high-sensitivity sensor spatial surveying of stream temperature. In streams with cobbly or bedrock-lined streambeds and variable bathymetry, use of FO-DTS to measure temperature close to the surface water and groundwater interface can be challenging. Differences between the methods were only significant near the stream banks in areas with shallower water and lower data density.
    - Mohamed et al. (2021b) developed improved geostatistical interpolation of streambed hydrologic attributes with addition of left censored data and anisotropy. Mapping methods for spatial interpolation under data-limited conditions can be challenging, especially for constrained environments such as streams and rivers, which exhibit mapping errors due to low point-measurement data density and clustering. Point measurements (i.e., hydraulic conductivity, seepage flux, and mercury solute flux) were collected along a study reach of East Fork Poplar Creek, Tennessee, and geostatistical mapping results were compared with and without anisotropy and left censored data addition. Adding left censored data increased the data density to recommended ranges, reduced data clustering, increased the spatial dependence for some attributes, and reduced the standard error for each of the three attributes. Addition of the left censored values resulted in a larger error reduction than the consideration of anisotropy.
    - Markovich et al. (2021) produced a mountain-front recharge (MFR) component characterization approach combining groundwater age distributions, noble gas thermometry, and fluid and energy transport modeling. Noble gas isotope age-dating is a novel approach that spans a wide range of ages, however assuming constant recharge temperature lapse rates with noble gas thermometry produced improbable recharge elevations. Numerical experiments suggest that surface

MFR, if derived from snowmelt, can locally suppress water table temperatures in the basin-fill aquifer, with implications for recharge elevations estimated from noble gas thermometry.

- Application of machine learning methods
    - Jiang et al. (2021) developed analysis and prediction of oil & gas produced water quantity and quality in the Permian Basin using machine learning. The prediction results from five-fold cross-validation showed that the Random Forest Regression model reported high prediction accuracy. The AutoRegressive Integrated Moving Average model showed good results for predicting produced water volume in time series.

University of California-Davis (Majdi Abou Najm)

- Modeling infiltration for water-repellent soils
    - Completed and tested the model successfully with great improvement on over 100 infiltration experiment
    - Publish findings in Water Resources Research Journal
    - Collaborate with researchers from Virginia Tech, France and Italy to adapt this model on the BEST infiltration model, successfully leading into another journal publication

- Modeling plant response to different light treatments
    - Completed and validated the model successfully with secondary data from the literature
    - Generated first draft of the manuscript with plan to submit in 2022

Utah State University (Scott Jones, Morteza Sadeghi, and David Robinson)

- Based on feedback from sensor manufacturers, developed a framework describing electromagnetic sensors based on key characteristics including measurement domain and method, theoretical basis and sensor electrode configuration of electromagnetic sensors in order to advance sensor quality testing standards.

Texas A&M University (Binayak Mohanty)

- Yang et al. (2021) studied the effects of water retention curves (WRCs) and permeability equations on the prediction of relative air permeability. Finding suggests that for disturbed soils, air permeability is primarily dictated by the pore tortuosity-connectivity but not the pore size distribution inferred from the WRCs.
- Wang et al (2021) developed a semi-analytical solution of the modified two-dimensional diffusive root growth model. The modified diffusive root growth model can be used to simulate the two-dimensional root growth during the crop growing period.

North Carolina State University (Josh Heitman) and Iowa State University (Robert Horton)

- Based on an extended de Vries model, a thermo-TDR sensor estimated soil bulk density (ρ_b) values well. Ignoring root contributions to bulk soil heat capacity introduced 7%, 14% and 14% errors in thermo-TDR estimated ρ_b values for loamy sand, sandy loam, and clay loam soils, respectively. A critical root density of 0.04 g cm^3 was determined beyond which roots may induce ρ_b errors greater than 0.1 g cm^3 with the thermo-TDR technique.

- We developed a framework to develop bulk density-associated pedo-transfer functions (PTFs) to describe soil water retention curves (SWRCs). The newly developed PTFs provided reliable WRC estimates for the validation datasets, with mean RMSE values of 0.055 and 0.059 cm^3 cm^{-3}, respectively. The accuracy of the new PTFs was comparable to or better than other PTFs. The new PTFs have the potential to be integrated into crop and soil management models to represent bulk density impacts on WRCs under field conditions.
- The cylindrical-perfect-conductors (CPC) theory was evaluated with a large heat pulse (HP) sensor of dissimilar probes. Results indicated that the CPC theory effectively accounted for the errors caused by the finite properties of the HP sensor. Thus, the CPC theory was recommended for estimating soil thermal properties with large HP sensors.
- A new dual-probe heat pulse (DPHP) sensor was developed to simultaneously measure soil thermal properties, soil water content and soil water matric potential. A series of experiments were performed to evaluate the sensor performance. The new sensor was able to measure each soil property with acceptable accuracy. The accuracy of the matric potential determinations was approximately 10% in log scale. The effective range for ψ measurements was − 1000 to − 2.5 m of water, and the accuracy of the ψ determinations was best between − 350 and − 2.5 m of water, which included values of field capacity and wilting point for most soils and crops. The sensor design included a single heater wire to provide simultaneous heat inputs to two different materials, i.e., the soil and the sensor porous medium. The single heater wire did not influence sensor accuracy as long as the soil and the sensor porous medium thermal conductivity values were not significantly different. The new DPHP based sensor effectively measured soil water matric potential, soil water content, and soil thermal property values.

University of Kentucky (Ole Wendroth)

- Testing a soil water content monitoring system for daily soil water balance component estimation
- Testing the technicality, use and precision of a VRI system.
- First attempts of using RZWQM2 for simulating soil water and crop growth dynamics under VRI in a farmer's field.

Oregon State University (Carlos Ochoa)

- Expanded soil moisture, surface, and groundwater monitoring network in riparian areas and pastures in the Oak Creek watershed in Corvallis, OR.
- Expanded a soil moisture-monitoring network in rangeland juniper-dominated systems in central Oregon.
- Established soil moisture and weather-telemetry network in a study site in eastern Oregon.

Washington State University (Markus Flury)

- There is an increased interest in the use of soil-biodegradable plastic mulch due to limited disposal options for conventional polyethylene mulch. However, information about the impact of continuous use of soil-biodegradable plastic mulch on the environment is limited. We investigated the effects on soil and groundwater quality from the use of soil-biodegradable plastic mulches for crop production for four consecutive seasons. Within

the four-year period, the soil-biodegradable plastic mulches had overall positive effects on soil and groundwater quality, except for reduced burst microbial respiration, which was more pronounced in Mount Vernon.
- We also investigated how biodegradable plastic mulches deteriorate and degrade in a natural soil environment. We characterized and quantified the chemical changes occurring in plastic mulches over time when exposed to sunlight and soil conditions. We found that the changes of physicochemical properties were affected by polymeric composition, and faster degradation occurred in warmer climates. These results help to better design biodegradable plastics for optimal in soil degradation.

The University of Arizona (Markus Tuller)
- Developed a new deep learning approach to forecast evapotranspiration from ground and remote sensing observations to aid with real-time estimation of crop water demand and irrigation water allocation in agriculture.

Texas A&M University (Briana Wyatt)
- Tested novel lithium-foil cosmic ray neutron sensor for estimation of field-scale soil moisture

University of Wyoming (Thijs Kelleners)
- Incorporation of seismic refraction first arrival times into an existing inverse modeling framework for estimating subsurface hydraulic properties
- Application of the brute force technique to identify optimum hydraulic parameters for a mountain hillslope using time-lapse electrical resistivity tomography data

USDA-ARS, Bushland, Texas (Schwartz and Evett)
- Sixth season of multi-location tests in semi-arid to humid climates of the integrated Irrigation Scheduling Supervisory Control and Data Acquisition (ISSCADA) system indicated positive outcomes for the system and system components. The ISSCADA patent is licensed by Valmont Industries, Inc. for use with their center pivot irrigation systems, including their variable rate irrigation systems. Several related presentations were made at the 6th Decennial National Irrigation Symposium, December 2021 (Andrade et al., 2021a,b; Evett et al. 2021a,b; Marek et al., 2021; O'Shaughnessy et al, 2021; Stone et al., 2021; Sui et al., 2021; Vories et al., 2021).
- A completely redesigned 2021 commercial version of the node and gateway system for wireless transmission of SDI-12 sensor data from field to the Internet was introduced by Acclima, Inc., and tested nationally and internationally.
- New TDR-315N and TDR-310N soil water, temperature and bulk EC sensors were introduced by Acclima, Inc.

Virginia Tech (Ryan Stewart)
- Used a new methodology to use time-lapse ground penetrating radar measurements to visualize and quantify the extent of infiltration under ponded water supply.
- Published a simple correction factor to improve infiltration models in soils with time-varying water repellency.
- Verified a new passive device for collecting water samples from surface runoff plots.

- Performed a study to examine differences in infiltration and soil water content under different soil surface coatings designed to better manage water availability in vineyard soils.
- Analyzed potassium concentrations in soil, petiole, and leaf samples for wine grape plants from 39 vineyard blocks to determine best soil sampling and analysis methods.

Kansas State University (Andres Patrignani)

- Validated a new cosmic-ray neutron detector based on lithium-foil that provides an alternative to more expensive helium-based detectors.
- Measuring rootzone in cropland fields usually requires multiple pronged sensors or expensive multi-depth profile-level sensors. We tested a well-known exponential filter commonly used for remote sensing applications to estimate soil moisture.
- Calibrated and validate soil water reflectometers used by the Kansas Mesonet. The calibration provides a universal correction for all sensors across more than 40 stations and soil textures.

Objective 3: Integrate scale-appropriate methods to improve decisions related to the management of soil and water resources.

University of California Riverside (Hoori Ajami)

- Develop watershed scale models to assess the impacts of climate variability and agricultural management practices on streamflow and lake-groundwater interaction

University of Wisconsin-Madison (Jingyi Huang)

- New index developed for assessing and forecasting agricultural and meteorological drought across the continental US using remote sensing data and land surface parameters.
- Presentations given to growers and agricultural research stations in Wisconsin on using remote sensing and soil moisture sensors for irrigation management and crop management

Texas A&M University (Binayak Mohanty)

- Sehgal et al. (2021b) developed a global flash drought monitoring tool using surface soil moisture from SMAP satellite. This tool is now being used by many across the globe for operational drought monitoring and management.

North Carolina State University (Josh Heitman) and Iowa State University (Robert Horton)

- We compared seed germination of four plant species in polyethylene glycol (PEG) and four soils with different textures under six water potentials under controlled laboratory conditions. Total seed germination for all species significantly differed between soil and PEG under the same water potentials, as well as among soil water potentials for each of PEG and soil materials. Caution must be used when considering results obtained using PEG solutions to infer germination behavior under field conditions.
- We evaluated biomass yield and water-use efficiency of perennial and annual bioenergy crops during 2 years in the North Carolina Piedmont. Results suggest that for the NC Piedmont region, land conversion from fescue hay production to bioenergy crops with

taller, higher yielding grasses would allow for greater biomass return on the amount of available water during a growing season. This information can aid growers when making management decisions about converting land into bioenergy crops.

- Soil physical disturbance and remediation practices including removal of topsoil, subsoil tillage and replacement of topsoil were investigated in a soybean–corn rotation field, which was located within a pipeline installation area. Soil bulk density, soil cone index and crop yields (soybean and corn) in the trafficked area and an adjacent unaffected area were compared at one year and two years after pipeline installation. Compared to yield data from the adjacent unaffected area, the pipeline disturbed area had statistically significant ($p < .05$) crop yield declines of 25% in soybean and 15% in corn. The near-term soil physical properties and crop yield were improved by subsoil tillage applied in the affected zones; however, a full recovery was not achieved within a 2-year period.

North Dakota State University (Aaron Daigh)

- Using our integrated remote sensing and machine learning algorithm, we were able to map high-resolution soil moisture in the Red River Valley (RRV) with RMSE within the range of common in-situ soil moisture sensors (<0.05 m^3 m^{-3}). The RRV land use is a mosaic of agricultural crops with seasonally frozen, smectitic soils. Validation of the algorithm was able to predict soil moisture across the growing season of 11 crops with an RMSE of 0.05 m^3 m^{-3} and r^2 of 0.70.

Washington State University (Markus Flury)

- The amount of plastic particles in terrestrial ecosystems is not well known, not only because it is difficult to ex- tract and identify plastic particles from terrestrial samples, but also because it is challenging to take representative samples from soils or sediments. We simulated how to take representative terrestrial samples to quantify plastic particles, and we evaluated the accuracy (error) of reported plastic concentrations in the literature. We developed a new method to take representative sample from the field. This method consists of taking replicated samples with each sample as large as possible (e.g., 1 m × 1 m) rather than multiple small cores, and then reduce the soil volume by the quartering method. This new method will allow for standardized soil sampling for future studies.

Texas A&M University (Briana Wyatt)

- Developed statistical seasonal streamflow forecasting models for irrigation districts and watersheds in OK, KS, and NE to aid in improving surface water management.

University of California-Riverside (Jirka Šimůnek)

The Use of Hydrus Models to Evaluate Various Irrigation and Fertigation Problems - Agricultural Applications

- Braunack et al. (2021) evaluated a Sprayable Biodegradable Polymer Membrane (SBPM) Technology for soil water conservation in tomato and watermelon production systems in Australia.
- Gohardoust et al. (2021) adapted and validated the ParSWMS numerical code (a parallelized version of HYDRUS-3D) for simulation of water flow and solute transport in soilless greenhouse substrates.

- Brunetti et al. (2021) carried out a comprehensive experimental and numerical (using a mechanistic soil-plant uptake model; the DPU module of HYDRUS) analysis on the translocation of carbamazepine (taken up by plant roots from the soil) in green pea plants.
- Brunetti et al. (2021) updated the DPU module of HYDRUS to develop a novel multiscale biophysical model to predict the fate of ionisable compounds in the soil-plant continuum.
- Noguchi et al. (2021) evaluated various subsurface drip irrigation designs in a soil profile with a capillary barrier using HYDRUS (2D/3D).
- Sao et al. (2021) carried out a numerical analysis of soil water dynamics during spinach cultivation in a soil column with an artificial capillary barrier under different irrigation managements using HYDRUS (2D/3D).
- Groenveld et al. (2021) used numerical modeling with HYDRUS-1D to optimize nitrogen fertigation with consideration of transient drought and nitrogen stress.
- Zhang et al. (2021) evaluated (using experimental data and HYDRUS (2D/3D) modeling) soil salt dynamics in brackish water dripped field leached with freshwater irrigation during different growth stages.
- Chen et al. (2021) evaluated (using experimental data and HYDRUS (2D/3D) modeling) the effects of biodegradable and plastic film mulching on soil temperature in a drip-irrigated field.
- Phogat et al. (2021) used the UnsatChem module of HYDRUS to assess how to managing salinity and sodicity risks of long-term use of recycled water for irrigation of horticultural crops.
- Helalia et al. (2021) evaluated the impact of drought and changing water sources on water use and soil salinity of almond and pistachio orchards using experimental data.
- Helalia et al. (2021) evaluated the impact of drought and changing water sources on water use and soil salinity of almond and pistachio orchards usig HYDRUS modeling.
- Farooq et al. (2021) evaluated the performance of HYDRUS-1D by calibrating and validating the model results for vertical movement of water and salts using saline irrigation water under greenhouse conditions.
- Farooq et al. (2021) studied interactive effects of saline water irrigation and nitrogen fertilization on tomato growth and yield.
- Khan et al. (2021) evaluated the performance of spring and summer-sown maize under different irrigation strategies in Pakistan.

Fate and Transport of Various Substances (Carbon Nanotubes, Viruses, Explosives)
With another member of the W4188 group (Scott Bradford) we worked on various aspects of the transport of pathogens in the subsurface.

- Zhang et al. (2021) evaluated using HYDRUS-1D non-monotonic contribution of nonionic surfactant on the retention of functionalized multi-walled carbon nanotubes in porous media.
- Sasidharan et al (2021) carried out a modeling study using HYDRUS (2D/3D) to evaluate virus transport from drywells under constant head conditions.

<u>Virginia Tech (Ryan Stewart)</u>

- Published new guidelines for installation of water quality sensors in headwater stream systems.

Oklahoma State University (Tyson Ochsner)

- Completed initial evaluations of seasonal streamflow forecasts utilizing both remotely sensed soil moisture and remotely sensed terrestrial water storage data.

Impacts

University of California-Riverside (Amir Haghverdi)
The UCRWATER research team (in collaboration with a local CE advisor) organized a workshop for growers in the southern California region to introduce the SAMZ-Desert tool and discuss the benefits, strengths and limitations of site-specific variable rate irrigation systems.

Michigan State University (Wei Zhang)
Our research identified stomatal internalization as an important mechanism for foliar uptake of silver nanoparticle. We also elucidated plant uptake of antibiotics, and bacterial community assembly and ARG changes in responding to antibiotic exposure in soil-lettuce system. These knowledge will help develop environmental-friendly agricultural nanotechnology, responsibly use reclaimed water for irrigation, protect soil quality, and ensure food safety.

University of California Riverside (Hoori Ajami)
This research has focused on understanding of groundwater recharge processes in mountain catchments and quantifying groundwater response time to meteorological droughts. As part of these efforts, we shared our research results with stakeholders such as NGOs and Groundwater Sustainability agencies in the Kaweah River watershed in Southern Sierra Nevada. This information will be valuable for sustainable water resource management in California and elsewhere. We also developed educational materials related to Hydrology and GIS for high school teachers. These materials are valuable to train the next generation of hydrologic scientists.

New Mexico State University (Kenneth Carroll)
Soil, and subsurface in general, is heterogeneous, which limits our understanding of water flow and solute transport. Since groundwater is a drinking water source and we use both surface and groundwater for agriculture, we strive to improve our characterization and quantification of water flow and reactive transport within hyporheic zones, soils, and groundwater systems. Geophysical methods are noninvasive and nondestructive subsurface imaging and characterization methods, which we are developing for hydrologic applications. We leverage and advance simulation including numerical modeling and machine learning. We are characterizing the occurrence, transport, and fate of emerging and recalcitrant contaminants. Results are improving our water supply and water quality sustainability. This will allow us to better manage water resources, water quality, and ecosystems.

University of California-Davis (Majdi Abou Najm)

- We developed, validated and published a model for infiltration of water-repellent soils, a phenomenon that we see more often with increased fires. We developed and valeted a model to predict plant response to different light treatments including changes to transpiration and water use efficiency. This can have major impact on the developments in agrivoltaics and other leading food and energy co-generation solutions. We completed drafts for two reviews (one critical and one systematic) related to soil structure and health, incorporating the screening of thousands of journal articles and the development of two large global datasets that will be made available. We published a generic regional model for resource optimization and management at the scale of water-energy-food nexus.

Utah State University (Scott Jones, Morteza Sadeghi, and David Robinson)

- Morteza Sadeghi and Scott Jones received $20,000 from the Utah State University Office of Research for their proposal titled, "Development of Novel Physics-Constrained Machine Learning Algorithms to Model Complex Soil Water Flow Processes". This grant, awarded in April 2021 and extended to 2 years due to complications of the pandemic, partially supports the sabbatical of Asghar Ghorbani, applied mathematics assistant professor, from Ferdowsi University of Mashhad, Iran.
- Our Western Soil Physics Working Group was awarded the **2021 Excellence in Multistate Research Award** for their sixty years of collaborative research, presently under their project titled, "W-4188 Soil, Water, and Environmental Physics to Sustain Agriculture and Natural Resources".
- The Sadeghi et al., 2017 "OPtical TRApezoid Model (OPTRAM)" for estimation of soil moisture based on remotely sensed shortwave infrared reflectance has been cited over 150 times and read over 7600 times in Research Gate and continues to be applied to a wide variety of remote sensing applications globally.
- The Borrelli et al paper 2020 "Land use and climate change impacts on global soil erosion by water (2015-2070)" has been cited 20 times and has an Altmetric score of 319 in the 3 months since publication.

University of Wisconsin-Madison (Jingyi Huang)

- Presentations at the 2021 ASA-CSSA-SSSA Annual Meeting.
- Presentations at the 2021 American Geophysical Union Annual Meeting.

Texas A&M University (Binayak Mohanty)

Our implementation of satellite platforms for Earth surface's soil moisture spatio-temporal distributions, dry down patterns, and associated hydrologic fluxes estimation, and linked numerical models have provided unprecedented tools and techniques to address wide spectrum of challenges related to soil and environmental sciences, including water management, crop production, climate forecasts, flood and drought prediction, groundwater recharge estimation, and pollution control.

North Carolina State University (Josh Heitman) and Iowa State University (Robert Horton)

Our method to derive soil water retention curves from soil thermal and electrical properties offers transformative potential for wide ranging investigations and new understanding of land surface, hydrologic cycle, and ecosystem dynamics.

University of Delaware (Yan Jin)

- The fundamental understanding of the bacterial EPS-driven hydro-physical changes of soil provides insights to effectively manage the green water to achieve sustainability in agriculture.
- Linking soil structure and water dynamics to soil carbon dynamics provides a new way of gaining mechanistic understanding of hot spots and hot moments of greenhouse gas emissions and a potential new approach to upscale pore-scale research on soil carbon dynamics.
- Understanding the contribution of Fe-speciation and crystallinity on the dynamics of size-fractionated colloids and colloidal organic carbon is critical for better predicting the cycling, transport, and stability of SOC in a redox fluctuating wetland.
- By examining the effects of salinity and redox changes, due to flooding and sea level rise, on the physical, hydrological, and chemical properties of soils, we will be able to forecast how these factors will impact utility and suitability for military operations and mobility along affected coastal regions.
- Understanding the mechanisms of plant root-soil interactions provide new insights for water and nutrient management in agricultural and natural systems.
- By identifying colloid-facilitated transport of weathering elements in stream water, we identified a new way or capability in predicting and regulating water quality in the downstream environments.

University of Kentucky (Ole Wendroth)

- Since these are ongoing initial investigations with a brand-new technology, we have not yet presented results to farmers at field days, but plan to do so for the year 2022. At the same time, we have developed a simple irrigation calculator that requires as input the soil type and the current soil water status. It estimates the root zone depth and gives a recommendation whether or not to turn on the irrigation system. As soon as this calculator is tested in the field, we will offer it to growers. Variable rate irrigation helps to save precious water resources and avoid surface runoff and pollution. Variable rate nitrogen application will help avoiding over-fertilization, and minimize nitrous gas emissions. Key benefits are healthier food and a healthy environment. At this stage, one PhD, one MS, and one visiting PhD student started their work on VRI simulations, and experimental planning for VRI- and VRN application. In 2022, a strip experiment will be conducted under the variable rate irrigation center pivot in which uniform versus variable rate nitrogen and water management will be tested.
- Major challenge will be the sensing of crop nitrogen status. We will approach this problem with drones and high-tech cameras. In year 1, there existed still some initial problems with the VRI pivot system, and the full understanding of the manufacturer's hard and software. These problems have been resolved to some part and the remaining ones will be tackled.

North Dakota State University (Aaron Daigh)

- The development of an integrated remote sensing and machine learning algorithm for accurate predictions of near-surface soil moisture results in a new tool to readily map water across the Red River Valley of the North where the agricultural landscape produces

a mosaic of crop species. This work and the transfer of knowledge to producers and other stakeholders will result in improved ability for precision agricultural, including precision harvesting to avoid deep wheel-traffic compaction.

- A challenge to urban storm water bioretention systems in frigid regions is the combined influences of salt (i.e., natural and de-icing agents) and petroleum product contamination. The research on sedge and ornamental grass species will inform urban planners and homeowners of science-based options for simultaneously obtaining aesthetic green spaces, plant survival, flood control, and sediment and contaminate removal from stormwaters
- The quantification of landslide conditioning factors for North Dakota's 24,000+ identified slope failures provides the foundation for future landslide risk mapping that is calibrated to its geographical regions and landscape conditions (semi-arid, continental climate, frigid and saline soils). The research will inform a broad range of stakeholders in the state for future planning of operations and land use to ensure human safety and minimize infrastructure damages.

Oregon State University (Carlos Ochoa)

- Understanding the dynamics of soil water transport through the vadose zone and into the shallow aquifer in rangeland ecosystems provides critical information regarding the potential for shallow groundwater recharge in arid and semiarid landscapes of the Pacific Northwest.
- Understanding the dynamics of soil water transport through the vadose zone and into the shallow aquifer in agroecosystems connected to riparian areas helps understanding potential hydrologic flow paths that may affect water quality in the stream.

Washington State University (Markus Flury)

- We provide, for the first time, quantitative data on plastic concentration in soils. As there is little information about how much plastics is in soils and how toxic that could be; this is important information for the broader public. We also provide justification for the use of biodegradable plastic in agriculture, and we argue that conventional plastics should be replaced with biodegradable plastics for single-use items, such as plastic mulch films. We have disseminated this information to the broader public via several podcast and newspaper interviews.

The University of Arizona (Markus Tuller)

- The OPtical TRApezoid Model (OPTRAM) for estimation of soil moisture based on remotely sensed transformed SWIR surface reflectance that we developed in 2017 in collaboration with Utah State University *(Morteza Sadeghi and Scott Jones)* has been applied in numerous research projects in 2021.
- In 2021 our advanced X-Ray CT segmentation algorithms that we developed over the past years have aided other researchers with projects that utilize X-Ray CT for soil and porous media research.

New Mexico State University (Manoj Shukla)

- The project on "water use efficiency improvement using micro-gravity drip irrigation system. A research and demonstration experiment is started in Leyedecker Plant Science

Center of NMSU. Because of the simplicity, ease of operation, it is expected that more and more people will use it for irrigating their crops. This system has the potential to shift irrigation from flood to more efficient micro-gravity drip irrigation system

- The project on "**brackish groundwater and RO concentrate reuse for agriculture"** is important for water scarce New Mexico. Appropriate use of saline water will augment irrigation water portfolio, and could help achieve the USDA's mission of food security. The improvement in the soluble sugar content of tomato showed that salinity can be used as a value added product.

Texas A&M University (Briana Wyatt)

- Improved knowledge and predictability of seasonal-scale streamflow trends for management of surface water resources. Potential to improve irrigation water allocation decisions, prevent flooding, and inform management decision during drought.
- Novel lithium foil cosmic ray neutron sensor for field-scale detection of soil moisture presents less expensive alternative to currently available sensors. Potential for increased adoption of this technology for improved water management in agriculture and other sectors.

University of Idaho (Robert Heinse)

- Understanding the mechanisms governing the dynamics of capillary driven water distributions are critical to predicting root-zone performance for plant-based bioregenerative life support during space travel and on planetary habitats.
- Identifying source areas for water intrusion leading to mine discharge are essential to minimize the environmental footprint of mining operations and its adverse effects in the Bunker Hill Superfund Site.

University of Wyoming (Thijs Kelleners)

- Monitoring of snow, soil, groundwater, and streamflow conditions in mountain and basin ecosystems, combined with numerical (sub-)surface flow modeling, is used to better understand water storage and flux dynamics under current conditions and future scenarios. The resulting data and computer simulation models facilitate improved decision making to maintain ecosystem health and support human activities related to agriculture, industry, cities, and recreation
- A new Decagon Devices WP4C dewpoint potentiometer was obtained through an equipment grant of $8,000 through the Wyoming Agricultural Experiment Station

University of California-Riverside (Jirka Šimůnek)

The HYDRUS models are continuously being updated based on the basic research carried out by the W4188 group. The HYDRUS-1D model was downloaded more than ten thousand times in 2021, and over fifty thousand HYDRUS users from all over the world registered at the HYDRUS website. We continue supporting all these HYDRUS users from the USA and around the world at the HYDRUS website using various tools, such as Discussion forums, FAQ sections, and by continuously updating and expanding a library of HYDRUS projects.

Additionally, we have added new capabilities to rigorously consider processes in the soil profiles with furrows (the Furrow module), to calculate cosmic-ray neutron fluxes (the Cosmic module), to simulate the translocation and transformation of chemicals in the soil-plant continuum (A

Dynamic Plant Uptake module), and to consider the transport of PFAS in the vadose zone (the PFAS). Finally, in 2020 we have offered two short courses on using HYDRUS models for Asian and European audiences. About 55 students participated in these short courses.

USDA-ARS, Bushland, Texas (Schwartz and Evett)

- The 2021 version of the node and gateway system developed with Acclima, Inc., was made commercially available. The Precision Sustainable Agriculture (PSA) project deployed the system on ~150 farms with 120+ scientists in 25 states. Microsoft integrated the PSA IoT technologies into their FarmBeats software. Public facing website: https://precisionsustainableag.org/ ICARDA/FAO have adopted the technology and Acclima sensors in their Near East and North Africa (NENA) Agricultural Evapotranspiration Network.
- Improved TDR soil water sensors were commercially available in 2021 (Acclima Inc. models TDR-315N, TDR-310N).
- Improved node and gateway hardware and firmware were made available in 2021 (Acclima, Inc. models Solar-Node and Solar-Gateway.
- Texas A&M personnel were trained to install, maintain, and read soil water sensing systems using the Acclima node and gateway wireless system, and the system and Acclima sensors were deployed and determined soil water content and bulk EC variations resulting from different prototypes of subsurface drainage systems.
- Regional, national and international requests to speak indicate considerable impact on evapotranspiration and soil water monitoring and irrigation management, including sensor-based irrigation management, subsurface drip irrigation and variable rate irrigation, and watershed management.

Virginia Tech (Ryan Stewart)

The Virginia wine industry is expanding in terms of wine grape production and sales. The 300th winery just opened, placing Virginia at 8th in the country. Concurrent efforts are also underway to expand wine grape acreage, including conversion of former tobacco lands in the southern portion of state. However, production of high-quality fruit can be a challenge due to the state's humid climate, which can increase disease pressure and provide excess water to the plants. At the same time, local soils often provide excess potassium to grapevines, which can raise fruit pH and make it more difficult for winemakers to create world-class wines. Understanding the soil properties that contribute to vine growth and changes in fruit composition will help growers to better manage their soil and grow top-quality wine grapes. With funding from the Virginia Wine Board and the Virginia Ag Council, a team of researchers from the Virginia Tech School of Plant and Environmental Sciences (SPES) and the Alson H. Smith Agricultural Research and Extension Center (AHS AREC) performed several studies to quantify and understand interactions between soil properties, water and potassium uptake, and wine grape properties. In 2021, the team collected 144 soil, 182 plant, and 72 fruit samples from 11 Virginia vineyards, including in-depth sampling at 3 vineyards in the state. The team also collected data and observations during winter pruning of the vines. The tissue samples were analyzed for nutrients and carbon isotopes (for vine water status). Soil samples were analyzed for potassium, pH, and organic matter. Fruit samples were analyzed for basic harvest chemistry including pH, titratable acidity, and sugars. The team also collected pilot data on different commercial products designed for reducing water infiltration into soil, which could enhance growers' ability to appropriately

manage soil water content for optimum fruit quality. The study results showed that topsoil thickness correlates with fruit acidity and sugars as well as vine size. Also, the team determined that the best soil sampling strategy for estimating plant-available potassium is collecting deep samples (0-38 cm) and using Mehlich-1 extraction on non-dried soils. Unexpectedly, the analysis indicated that whole leaf samples are better correlated with soil potassium than the current grower standard of just using the petiole portion of the leaf. These results have been shared with other scientists and with wine-grape growers via 5 presentations, as well as individual results and nutrient recommendations sent to each collaborating grower. Findings are being prepared for publication in Extension bulletins as well as peer-reviewed journal articles.

Oklahoma State University (Tyson Ochsner)

- This research included scientific and career mentoring for one PhD student and led to a research grant from the US Bureau of Reclamation.

Kansas State University (Andres Patrignani)

- The hydrological network deployed within the Konza Prairie trained 4 research scholars from Argentina and Uruguay, a visiting undergraduate student from Tufts University, and enabled environmental monitoring of NSF LTER sites.
- On-farm research at the Flickner Innovation Farm was shared with the land owner and neighbors

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2. Shukla M.K. 2021. Sustainable use of brackish water for arid agriculture. 4th annual WIN workshop, BGNDRF, Alamogordo.
3. Shukla, M. K., Annual Meeting, Soil Science Society America, Salt Lake City, Utah, "Irrigation with Brackish and Produced Waters: Impacts on Soil and Plant Environments in Arid Regions", Scope: International. (November 2021).
4. Shukla, M. K., Annual WIN Workshop, Brackish Groundwater National Desalination Research Facility, Alamogordo, "Irrigating Atriplex Species with Diluted Produced Water", Scope: National, Invited or Accepted? Invited. (September 2021).
5. Shukla, M. K., IICA-NMSU, AI Workshop, IICA, "IoT Monitoring System for Digital Agriculture at NMSU Leyendecker Science Center", Scope: International. (August 2021).
6. Shukla, M. K., Unitarian/Universal virtual Roundtable, Unitarian/Universal virtual Roundtable, "surface water scarcity for irrigation and variability of the quality of groundwater in New Mexico", Scope: Regional. (June 13, 2021).
7. Shukla, M. K., IICA-NMSU, AI Workshop for Livestock, IICA, "AI for Agriculture", Scope: International. (April 2021).
8. Babaeian, E., S. Paheding, N. Siddique, V.K. Devabhaktuni, and M. Tuller, 2021. Forecasting of Evapotranspiration from Ground and Remote Sensing Observations with Deep Learning. AGU Fall Meeting, New Orleans, LA, Dec. 13-17, 2021.
9. Babaeian, E., M.R. Gohardoust, and M. Tuller, 2021. High Resolution Three-Dimensional Mapping of Vegetation Water Content via Fusion of SWIR Reflectance and Canopy Laser Topography. AGU Fall Meeting, New Orleans, LA, Dec. 13-17, 2021.
10. Babaeian, E., S. Paheding, N. Siddique, V.K. Devabhaktuni, and M. Tuller, 2021. Application of Long Short-Term Memory Deep Learning for Forecasting of Evapotranspiration from Ground and Satellite Observations. ASA-CSSA-SSSA International Annual Meeting, Salt Lake City, UT, Nov. 7-10, 2021.
11. Babaeian, E., M.R. Gohardoust, and M. Tuller, 2021. A New Approach to Short-Wave Infrared Remote Sensing of Plant Canopy Water Content. ASA-CSSA-SSSA International Annual Meeting, Salt Lake City, UT, Nov. 7-10, 2021.
12. Bandai, T., M. Sadeghi, E. Babaeian, M. Tuller, S.B. Jones, and T.A. Ghezzehei, 2021. Characterization of Unsaturated Water Flow in Soils Using Short-Wave Infrared Imaging

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13. Ochoa, C.G., N. Durfee and T. Deboodt. Ecohydrologic relationships in juniper- and sagebrush-dominated landscapes. Society for Range Management – Annual Meeting. February 6–10, 2022. Albuquerque, NM.
14. Anaya-Espinoza, H.G., F. Villareal-Guerrero, C.G. Ochoa, J.A. Prieto-Amparán and C. Ortega-Ochoa. Assessing precipitation-vegetation-groundwater relationships in a rangeland watershed of northern Mexico. Society for Range Management – Annual Meeting. February 6–10, 2022. Albuquerque, NM.
15. R. Garduño, H., F. Villarreal, C.G. Ochoa, and N.S. Hernández. 2021. Escorrentías en una microcuenca del desierto Chihuahuense (Runoff in a small watershed in the Chihuahuan Desert). In *Proceedings of* V *Congreso Internacional* and XVIII *Congreso Nacional Sobre Recursos Bióticos De Zonas Áridas.*
16. Peterson, A., T.M. DeSutter, N.E. Derby, A.L.M. Daigh, and M. Meehan. 2021. Use of gypsum and calcium acetate for improving water flow in oilfield produced water-impacted soils. Environmental Quality – Oral Session. American Society of Agronomy Environmental Quality Section. *In Annual Meeting Abstracts.* ASA-CSSA-ASA Madison, WI.
17. Reicks, G., D.E. Clay, S.A. Clay, D.R. Joshi, J. Miller, S. Westhoff, A.L.M. Daigh, and S.A. Bruggeman. 2021. Winter cereal rye cover crop decreased nitrous oxide emissions during early spring. Environmental Quality – Oral Session. American Society of Agronomy Soil Carbon and Greenhouse Gas Emissions Community. *In Annual Meeting Abstracts*. ASA-CSSA-ASA Madison, WI.
18. Miller, J., S.A. Clay, D.E. Clay, D.R. Joshi, G. Reicks, S. Westhoff, and A.L.M. Daigh. 2021. Influence of rye cover crop on early corn growth, photosynthesis genes, and yield. American Society of Agronomy Agronomic Production Systems. *In Annual Meeting Abstracts*. ASA-CSSA-ASA Madison, WI.
19. Joshi, D.R., D.E. Clay, S.A. Clay, A.L.M. Daigh, J. Miller, G. Reicks, and S. Westhoff. 2021. Influence of rye residue on CO_2 and N_2O emissions, soil moisture and nutrient mineralization in corn cropping system. Environmental Quality – Oral Session. American Society of Agronomy Soil Carbon and Greenhouse Gas Emissions Community. *In Annual Meeting Abstracts*. ASA-CSSA-ASA Madison, WI.
20. Nelson, R., A.L.M. Daigh, and E.E. McGinnis. 2021. Perennial ornamental grasses survive repeated cycles of submergence in a simulated rain garden environment. School of Natural Resource Sciences Annual Symposium. November 1st, 2021
21. Nelson, R., E.E. McGinnis, and A.L.M. Daigh. 2021. Evaluation of ornamental grasses for rain garden environments. WERA-1013 Intermountain Regional Evaluation and Introduction of Native Plants multi-state project annual meeting (virtual). October, 29th, 2021.
22. Mohammed, M., T. Johnson, B. Ajmera, and A.L.M. Daigh. 2021. Effect of different salts on the liquid limit and plasticity index of clays. National Science Foundation Research Experience for Undergraduates Symposium, North Dakota State University. August 3rd, 2021. Fargo, North Dakota.
23. Wenaas, R., M. Finneseth, U. Acharya, B. Ajmera, and A.L.M. Daigh. 2021. Recent North Dakota slope failures and the effects of roads, rivers, precipitation, incline, sand,

and water tables. National Science Foundation Research Experience for Teachers Symposium, North Dakota State University. July 30th, 2021. Fargo, North Dakota.

24. Ajmera, B., K.R. Upadhaya, and A. Daigh. 2021. Slope failures in North Dakota: Influence of geology, topography and salt concentration in pore fluid. International Foundations Congress & Equipment Expo (IFCEE) – joint meetings of The International Association of Foundation Drilling, Deep Foundations Institute, Geo-Institute of American Society of Civil Engineers, and Pile Driving Contractors Association. Dallas, Texas.
25. Jia, X., K. Almen, A. Daigh, and T. Scherer. 2021. North Dakota Drainage Research. NCERA 217 Multistate Project Annual Meeting. Virtual April 8th, 2021.
26. Acharya, U., A.L.M. Daigh, and P. Oduor. 2021. Use of Landsat 8 Image and Meteorological Data to Map Soil Moisture in the Red River Valley. Soils and Crops Conference. *In Annual Meeting Abstracts.* Saskatchewan, CA. Virtual March 16th, 2021
27. Puffer, M.A., R.F. Limb, A.L.M. Daigh, K.K. Sedivec, and J. Volk. 2021. Variable topsoil depth: Returning heterogeneity to reclaimed grasslands. *In Annual Meeting Abstracts.* Society for Range Management. Virtual. Feb. 15th, 2021.
28. Puffer, M.A., R.F. Limb, A.L.M. Daigh, K.K. Sedivec, and J. Volk. 2021. Contemporary techniques used to address soil compaction on reclaimed grasslands. *In Annual Meeting Abstracts.* Society for Range Management. Virtual. Feb. 15th, 2021.
29. Lardy, J., T. DeSutter, M. Meehan, N. Derby, K. Horsager, and A. Daigh. 2021. An examination of pipeline site-preparation methods for improving plant establishment. *In Annual Meeting Abstracts*. Manitoba Soil Science Society. Virtual Feb. 4th, 2021.
30. Jin Y. and S. Franklin, The unexplored role of preferential flow in soil carbon dynamics. Soil Science Society of America meeting, Symposium - Interactions between Chemistry, Physics, and (Micro)biology: Water, Pores, and Biota across Scales. Salt Lake City, November 7-10, 2021 (Invited).
31. Yan, J. and Y. Jin. Insight into colloid-mediated transport in catchments: a metadata analysis. (Poster) American Geophysical Union Conference, December 13-17, 2021.
32. Yan, J., S. Joshi, T. Ghezzehei, Y. Jin. Root redistribution of water to dry soil affects SOM mineralization. (Oral) Soil Science Society of America meeting, Salt Lake City, November 7-10, 2021.
33. Afsar M.Z., and Y. Jin. Soil hydraulic properties in vulnerable terrestrial ecosystems influenced by flooding and sea-level rise (Oral). Soil Science Society of America meeting, Salt Lake City, November 7-10, 2021.
34. Franklin, S., Vasilas, B., Jin, Y. Pores make pathways: Is connectivity the disconnect in upscaling efforts? (Oral) Soil Science Society of America International Meeting, Salt Lake City, UT, Nov. 7-10, 2021
35. Franklin, S.M., Kravchenko, A.N., Vargas, R., Vasilas, B., Fuhrmann, J.J., Jin, Y Preferential flow plays an unexplored role in the carbon cycle. 5th summer school on flow and transport in porous and fractured media. Cargèse, France July 20-31, 2021
36. Kaniz, F., Bais, H., and Jin, Y. Role of Bacillus Subtilis, A Plant Growth-Promoting Rhizobacteria, in Improving Soil Hydro-Physical Properties (Poster). InterPore, May 31-June4, 2021, Virtual Conference.
37. Kocian, L., and B.P. Mohanty, Evaluating the Presence of Preferential Flow Using Machine Learning Algorithms and Remote Sensing Data, AGU Fall Meeting Abstract, 2021.

38. Mbabazi, D., and B.P. Mohanty, Carbon-Water-Energy Coupling Relationships from the Field to Satellite Scale, AGU Fall Meeting Abstract, 2021.
39. Mohanty, B.P., D. Mbabazi, and V. Sehgal, Exploring Evapotranspiration-Soil Moisture Coupling Relationships from the Eddy Covariance to Satellite Scale, AGU Fall Meeting Abstract, 2021.
40. Hong, M., and B.P. Mohanty, Representing the Dupuit-Boussinesq Aquifer in the National Water Model: Catchment-Scale Application of Hydraulic Groundwater Theory, AGU Fall Meeting Abstract, 2021.
41. Hong, M., and B.P. Mohanty, A New Method for Effective Parametrization of Catchment-Scale Aquifer, AGU Fall Meeting Abstract, 2021.
42. Kathuria, D., B.P. Mohanty, and K-A. Cawse-Nicholson, STARFM-ML: A Novel Machine Learning Driven Approach to Fuse Remote Sensing Data, AGU Fall Meeting Abstract, 2021.
43. Sehgal, V., B.P. Mohanty, Introducing Open-Source Tool for Near-Real-Time Global Flash Drought Monitoring with SMAP, AGU Fall Meeting Abstract, 2021.
44. Sedaghatdoost, A., B.P. Mohanty, and Y. Huang, Subsurface Variation of Soil Physicochemical Properties and Redox-Sensitive Elements under Different Land Covers in Gulf Coastal Plains, AGU Fall Meeting Abstract, 2021.
45. Calabrese, S., B.P. Mohanty, and A. Malik, Soil Microorganisms Regulate Extracellular Enzyme Production to Maximize their Growth Rate, AGU Fall Meeting Abstract, 2021.
46. Jena, S., B.P. Mohanty, and R.K. Panda, Machine Learning Based Groundwater Level Predictions Using Dominant Hydrological, Geological, and Climatic factors in Data-Scarce Tropical Savanna Region of India, AGU Fall Meeting Abstract, 2021.
47. Wang, C., W. Sheng, J. Xu, D.A. Robinson and S.B. Jones, "Dielectrically Relaxing and Electrically Conducting Suspensions for Testing Water Content Sensors," 2021 13th International Conference on Electromagnetic Wave Interaction with Water and Moist Substances (ISEMA), 2021, pp. 1-4, doi: 10.1109/ISEMA49699.2021.9508307.
48. González-Teruel, J.D., S.B. Jones, J. Giménez-Gallego, D.A. Robinson, A. J. Lozano-Guerrero and R. Torres-Sánchez, "Evaluating a low-cost self-manufactured Coaxial Open-Ended Probe for the Measurement of the Complex Permittivity of Granular Media," 2021 13th International Conference on Electromagnetic Wave Interaction with Water and Moist Substances (ISEMA), 2021, pp. 1-6, doi: 10.1109/ISEMA49699.2021.9508322.
49. Skierucha, W., Kafarski, M., Wilczek, A., Szypłowska, A., Jones, S.B., Sabouroux, P., Robinson, D.A., Krupka, J. and Lewandowski, A., 2021, July. Towards standardization of electromagnetic soil moisture measurements. In 2021 13th International Conference on Electromagnetic Wave Interaction with Water and Moist Substances (ISEMA) (pp. 1-4). *IEEE.*
50. Jones, S.B., M. Sadeghi and D.A. Robinson W-4188 Multi-State Research Project, "Utah State University Report," USDA, Virtual Meeting, January 3-4, 2021.
51. Jones, S.B., W. Sheng, J. Xu, and D.A. Robinson. 2021. Dielectrically Relaxing and Electrically Conducting Suspensions for Testing Water Content Sensors. Proceedings of the 13th *International Conference on Electromagnetic Wave Interaction with Water and Moist Substances* (ISEMA; Virtual participation). Kiel, Germany. July 27-31, 2021.
52. Naruke, C., Mills, M., Blakeslee, A., Fatzinger, B., Bugbee, B., and Jones, S.B. (2021) Evaluation of alternative candidate plant growth media for reduced gravity applications.

Japanese Society of Soil Physics Annual Meeting, Oct. 29, 2021., Japan.

53. Jones, S.B., C. Naruke, J.J. Chen and W. Sheng. 2021. Standardizing Particulate Porous Media for Sensor Evaluation, Calibration and Validation. *ASA, CSSA, and SSSA International Annual Meetings*. Nov. 7-10, 2021.
54. Blakeslee, A., M.S. Mills, C. Naruke, W. Sheng and S.B. Jones. 2021. Automated Laser-Distance- and Pressure-Based Measurements for Characterizing Water Retention in Coarse Media. *ASA, CSSA, and SSSA International Annual Meetings.* Nov. 7-10, 2021.
55. Naruke, C., Fatzinger, B., Bugbee, B., and Jones, S.B. (2021) Impact of Root Growth on Water Retention and Hydraulic Properties in Containerized Soilless Media. *ASA, CSSA, SSSA International Annual Meeting*, Nov. 7-10, 2021., Salt Lake City, UT.
56. Mills, M.S. Naruke, C., and Jones, S.B. (2021) Characterizing Water Retention Novel Soilless Media for Reduced Gravity Applications. *ASA, CSSA, SSSA International Annual Meeting*, Nov. 7-10, 2021., Salt Lake City, UT.
57. Jones, S.B. 2021. Quality Assessment Needs for Soil Water Content Sensors. *13th International Conference on Agrophysics: Agriculture in Changing Climate*. Nov. 15-16, 2021.
58. Jones, S.B., A. Blakeslee, M.S. Mills and C. Naruke. 2021. Assessing the Significance of Hysteresis in Novel Porous Plant Growth Media. *AGU Fall Meeting Abstracts.* Dec. 13-17, 2021.
59. Naruke, C., A. Blakeslee and S.B. Jones 2021. Pore Space Dynamics and Oxygen Concentration in Containerized Porous Media. *AGU Fall Meeting Abstracts.* Dec. 13-17, 2021.
60. Jones, S.B., C. Naruke and W. Sheng. 2021. Standardizing Porous Media for Electromagnetic Water Content Sensor Evaluation, Calibration and Validation. *AGU Fall Meeting Abstracts.* Dec. 13-17, 2021.
61. Johnson, C., C. Stice, K.C. Carroll, J. Szecsody, and C.-H. Tsai (2022) Organic Gas Injection Delivery Behavior for Vadose Zone Remediation. Waste Management Symposium (WM2022), March 6-10, Phoenix, AZ. [Peer-Reviewed Conference Proceedings Paper]
62. Carroll, K.C. (2021) Multidisciplinary Hydrology: A Few Examples of Scientific Mixology. Invited Presentation: The University of Arizona Hydrology and Atmospheric Sciences Department Seminar, September 23.
63. Carroll, K.C., R.A.M. Mohamed, Chia-Hsing Tsai, S.C. Brooks, D. Rucker, and A. Ulery (2022) Comparison of Multiple Direct and Indirect Characterization Methods for Hyporheic Zone Exchange. Waste Management Symposium (WM2022), March 6-10, Phoenix, AZ.
64. Jamil, A., D.F. Rucker, S.R. Dipon, C.-H. Tsai, H. Cao, S. Brooks, and K.C. Carroll (2022) Evaluation of Machine Learning Algorithms for Subsurface Resistivity Predictions Based on Geophysical Electrical Resistivity Data and Characterization of Hydrogeological Conditions. Waste Management Symposium (WM2022), March 6-10, Phoenix, AZ.
65. Wu, L., J.D. Gomez-Velez, and K.C. Carroll (2021) Hyporheic exchange under seasonally connected groundwater surface-water systems. American Geophysical Union Fall Meeting, Fall Meeting Abstract.
66. Noyes, C., K.C. Carroll, R. Purtschert, G. Ferguson, J.C. McIntosh (2021) Using Argon-39, Noble Gases, and other Environmental Tracers to Infer Changes in Recharge to the

Semi-Arid Tucson Basin over the Holocene. American Geophysical Union Fall Meeting, Fall Meeting Abstract.

67. Stice, C., C.-H. Tsai, C. Johnson, and K.C. Carroll (2021) Numerical Modeling of Gas Flow in the Hanford Vadose Zone. American Geophysical Union Fall Meeting, Fall Meeting Abstract.
68. Mohamed, R.A.M. M. Hitzelberger, K.C. Carroll, N.A. Khan, M.L. Brusseau (2021) Modeling Back-Diffusion Impacts on Perfluorooctane Sulfonic Acid (PFOS) Contaminant Transport. RemPlex Summit 2021 Global Summit on Environmental Remediation, November 8-12, Virtual.
69. Tsai, C.-H., K.C. Carroll, D.F. Rucker, S.C. Brooks, and T. Ginn (2021) Coupled Stream-Groundwater Flow and Transport Modeling of Streambed Heterogeneity Impacts on Hyporheic Exchange. ASA, CSSA, and SSSA International Annual Meeting, Nov. 7-10, Salt Lake City, UT.
70. Mohamed, R.A.M., M. Hitzelberger, K.C. Carroll, M.L. Brusseau (2021) Characterization of One and Two Dimensional Transport of Perfluorooctane Sulfonic Acid in Homogeneous and Heterogeneous Sands. ASA, CSSA, and SSSA International Annual Meeting, Nov. 7-10, Salt Lake City, UT.
71. Rucker, D.F., K.C. Carroll, C.-H. Tsai, and A. Pearson (2021) Observing Streambed Infiltration Heterogeneity of an Intermittent River at the Onset of Flow with Electrical Resistivity and Buried Sensors. Annual Symposium – Arizona Hydrological Society, Phoenix, September 15–17.
72. McIntosh, J.C., K. Markovich, C. Noyes, L. Condon, G. Ferguson, K.C. Carroll, R. Purtschert (2021) Application of 3H, 85Kr, 39Ar, and 14C, noble gas thermometry, and modeling to constrain mountain-front recharge to basin-fill aquifers. Goldschmidt, Lyon, July 4-9.
73. Ginn, T., M. Aghababaei, K.C. Carroll, R. Gonzalez-Pinzon, A. Tartakovsky (2021) The Remarkable Generality of the Transient Storage Model with Residence Time Dependence: Temporal Moments. European Geophysical Union General Assembly, April 19-30.
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