Project Number: W-4188 (current) or W-TEMP5188 (temporary)

Project Title: Soil, Water, and Environmental Physics for a Sustainable and Resilient Future

Requested Project Duration: October 1, 2024 – September 30, 2029

Proposal Due Date: Jan. 16, 2024

Statement of Issue(s) and Justification:

Soil and the underlying vadose zone (in the remainder of this document, for simplicity, included in the term "soil") are critical components of the Earth system, maintaining plant and animal life, supporting food production, providing key ecosystem services, and being a critical storage, reaction, and transport medium for water, dissolved solutes, gasses, and pollutants. Soils (i.e., soils and their underlying vadose zone) regulate water, energy, and nutrient movement throughout the terrestrial system, sustaining life above and below ground. As demands for food and water increase, so do the demands placed on soil resources. In order to sustain soils and their key functions into the future, efforts must be made to steward and protect this non-renewable resource.

Soil physics plays a critical role in our understanding of the functions of soil in regulating mass and energy transport at the Earth's surface, and progress in recent years has led to an even greater appreciation of the complexity and heterogeneity of soils. From micropore to the continental scale, understanding and quantifying soil heterogeneity remains a key challenge. Yet, this heterogeneity is a determining factor in the fate of water, nutrients, and energy with the groundwater-soil-plant-atmosphere continuum. Much research has been done at moderate spatial scales (i.e., a single field or plot), but many questions remain regarding these processes at much finer scales (i.e., nm or smaller) and at larger spatial scales (i.e,. 100s of km or larger). Recent advances in technology have increased our ability to image soil at smaller scales, and increasing computational power allows simulations of water movement at the continental scale; still, much remains to be learned about this complex system.

Historically, the field of soil physics was concerned with issues of agricultural importance such as irrigation scheduling, nutrient management, and improving crop productivity. In recent years, that focus has remained but new foci have emerged, including emphases on interdisciplinary work related to the impacts and applications of soil physics in ecology, hydrology, geohydrology, biogeochemistry, climate science, and other related fields. This trend has been observed in the field at large but also has been seen quite clearly in the outputs from this multistate project, which has grown in the breadth of topics studied over the past decades.

The collaborations developed through this multistate project have affected multiple generations of soil physicists and other scientists with significant engagement in soil physics, and the continuation of the project will serve to maintain many of these relationships into the future while simultaneously creating a pathway for new scientists to join. From the collaborations within this group, the field of soil physics has been transformed by new fundamental knowledge and applications of this knowledge have been developed for broad societal and environmental benefit.

Members of this group tend to form and reform around new multi-investigator programs to address emerging critical questions for sustainable solutions to grand challenges. This flexible and synergistic approach has been extremely productive, and it encourages a rich pollination of ideas and solutions to complex problems. The multistate committee structure is a convenient and efficient platform for establishing national research collaborations, validating approaches and techniques, pooling data, creating rigorous peer reviews, sharing equipment and developing the next generation of highly-trained soil scientists, environmental scientists, and engineers. This renewal proposal seeks to maintain the ties between this extremely productive and creative group. Without the W5188 committee, the field would not be as focused on national needs research. The proposal also highlights our efforts to improve environmental monitoring, implement basic soil physics research, reach out to a broader scientific community (e.g., plant science, ecology, chemistry, and microbiology), and educate and communicate to stakeholders and colleagues within and outside our traditional disciplines.

Related, Current and Previous Work:

Though other active multistate research projects examine related soil, water quality, and water quantity issues, none of them focus on the interactions and feedbacks between soil physical and hydraulic properties, soil structure, energy and mass balances, soil health, and climate, and between soil/vadose zone processes and groundwater. Relevant multistate projects with some aspects similar to the proposed W5188 activities include:

- NC1034: Impact Analyses and Decision Strategies for Agricultural Research
- NC1178: Land use and management practice impacts on soil carbon and associated agroecosystems services
- NC1186: Water Management and Quality for Specialty Crop Production and Health
- NCAC1: Crop and Soil Research
- NC1195: Enhancing nitrogen utilization in corn based cropping systems to increase yield, improve profitability and minimize environmental impacts
- NC1198: Enhancing the Resilience of Agriculture and Food of the Middle: Building for the Future
- WDC52: Implementing and Correlating Soil Health Management and Assessment in Western States
- WERA1022: Irrigation Technologies and Scheduling for Water Conservation and Water Resources Management
- S1090: AI in Agroecosystems: Big Data and Smart Technology-Driven Sustainable Production
- SERA6: Methodology, Interpretation, and Implementation of Soil, Plant, Byproduct, and Water Analyses

- NCERA3: Soil and Landscape Assessment, Function and Interpretation
- NCERA59: Soil Organic Matter: Formation, Function and Management
- W4147: Managing Plant Microbe Interactions in Soil to Promote Sustainable Agriculture

- W508: Western Water Network for Agriculture and Water Smart Communities: Responding to Climate Change and Other Stressors to Water Resources

The results of the previous W4188 multistate project are extensive, timely, and applicable to numerous agricultural and environmental issues. With the national dialog further expanding to include impacts of climate change, links between population growth in the U.S. and land use change, the need for sustaining the health of soils, and the importance of soil to moderate and control the water budget and important ecological systems, the general themes of W5188 are even more critical. *There is consensus that the soil physics community can and should continue to pursue collaborative efforts,* so that our thus-far integrated knowledge and skills can be applied to sustainable agricultural and environmental practices, natural resource stewardship, and the adaptation to and mitigation of global climate change.

This project was the 2021 winner of the “Excellence in Multistate Research” award and represents the largest group of soil physics researchers in the U.S. outside of the Soil Science Society of America (SSSA) Soil Physics and Hydrology Division. This group was also recently recognized by the National Academies of Sciences, Engineering, and Medicine as being exemplary in working on issues of national importance to advance knowledge and provide clear economic, environmental, and social benefits.

The objectives of this multistate project are to: 1) Improve fundamental understanding of soil physical and vadose zone processes; 2) Apply soil physical and vadose zone concepts to improve soil and water management; 3) Develop new instrumentation, methodology, and models to characterize and interpret soil physical and vadose zone processes; and 4) Translate new concepts and methods to students, stakeholders, and the public.

List of Objectives:

1. **Improve fundamental understanding of soil physical and vadose zone processes**

   1.1. *Improve understanding of preferential flow and its role in biogeochemistry*

   1.2. *Study the role of soils in greenhouse gas emissions*

   1.3. *Dynamic changes in soil properties and influence on processes, including water retention, coupled heat and mass transfer processes (e.g., solutes, gasses, water)*

   1.4. *Surface energy balance and evapotranspiration*

   1.5. *Drivers of hydrologic change*

   1.6. *Water, solute, and heat flow in heterogeneous systems*

   1.7. *Deep vadose zone processes and linkages to groundwater*

   1.8. *Behaviors of emerging contaminants in soils*

2. Apply soil physical and vadose zone concepts to improve soil and water management

2.1. *Applications to address soil function and soil resiliency, including climate change mitigation*

2.2. *Address soil-related challenges within the water-food-energy-climate-environment nexus*

2.3. *Physics of non-soils growing media for food production on earth and at reduced gravity (on orbit, moon, Mars)*

2.4. *Applying soil physics to assess or improve soil health*

2.5. *Soil moisture and other soil sensing networks and their applications*

2.6. *Proximal and large-scale soil moisture sensing technologies*

3. Develop new instrumentation, methodology, and models to characterize and interpret soil physical and vadose zone processes

3.1. *Sensor development*

3.2. *Sensor protocols and evaluation/inter-comparison*

3.3. *Model-data fusion and integration for decision-support systems (including AI and robotics/IOT)*

3.4. *Development and parameterization of process-based models that simulate soil and vadose zone processes*

3.5. *Upscaling and downscaling of in situ, proximal, and remote sensing data for parameterization of models in the absence/scarcity of soil geodatabases*

3.6. *Apply geophysical tools to better quantify subsurface heterogeneity, hydrologically relevant properties, and groundwater and vadose zone interactions*

3.7. Integration of sensor data, remote sensing data, in situ measurements across scales into scale-appropriate data analysis, modeling, and decision-support tools

4. Translate new concepts and methods to students, stakeholders, and the public

4.1. *Making our science more actionable for stakeholders and decision makers through knowledge translation, extension, and public outreach*
4.2. *Open-access and reproducible science*
4.3. *Open-access educational resources*
4.4. *Improved pedagogy and teaching methods*
4.5. *K-12 outreach and education*
4.6. *Diversity, equity, and inclusion and improving recruitment, retention of students in soil physics, hydrology, and environmental sciences*
4.7. *Improving interdisciplinary interactions*

Description of Objectives:

1. Improve fundamental understanding of soil physical and vadose zone processes

1.1. Improve understanding of preferential flow and its role in biogeochemistry

Preferential flow is defined as the rapid and uneven movement of water and any solutes through the subsurface. There has been extensive research highlighting the prevalence of preferential flow in many different environments (e.g., Flury et al., 1994; Kodešová et al. 2012). Preferential flow has been implicated in the rapid transport of different contaminants such as pesticides and antibiotics (Radolinski et al., 2022; Schlögl et al., 2022), and increasing groundwater recharge (Kurtzman and Scanlon, 2011). Field and laboratory measurements have identified mechanisms leading to preferential flow, including soil shrinkage (Stewart et al., 2015), macropores such as insect burrows (Capowiez et al., 2015; Whalen et al., 2015), root channels (Johnson and Lehmann, 2006; Radolinski et al., 2018), and organic substances exuded from plant roots and micro-organisms (Benard et al., 2019, 2021). Complementary modeling work has depicted the effects of preferential flow on infiltration processes, water redistribution, and contaminant transport (e.g., Gerke and van Genuchten, 1993b; Köhne et al., 2006; Mair et al., 2022).

Comparatively little is known about how preferential flow paths affect biogeochemical processes in soil. In general, biogeochemical cycling is mediated by microbes and occurs within hotspots - i.e., locations with much faster processing rates - and hot moments - i.e., short-term events of accelerated change (McClain et al., 2003; Bernhardt et al., 2017). Water typically leads to the development of hot spots and moments (Krause et al., 2017), and soils directly surrounding preferential flow paths tend to have more carbon and nitrogen than the adjacent matrix soil (e.g., Bundt et al., 2001; Fuhrmann et al., 2019). These factors can lead to the presence of hotspots (Kuzyakov and Blagodatskaya, 2015) and localized high rates of microbial activity (Franklin et al., 2019) along preferential flow paths. Macropores can also lead to greater rates of gas exchange between the soil profile and atmosphere, with effects noted for both convective and diffusion transport processes. These findings point to the need to critically examine the role of preferential flow paths in the transport and transformations of water, gas, carbon, and nutrients.

1.2. Study the role of soils in greenhouse gas emissions

Atmospheric concentrations of most greenhouse gases are increasing rapidly. While much emphasis has been placed on rising CO_2 concentrations, methane (CH_4) and nitrous oxide (N_2O) are much more potent drivers of global warming. Current calculations hold that CH_4 has 30 times and N_2O has 270 times the warming potential of CO_2. Thus, it is critically important to study the role of soil physical properties and states (e.g., water potential and content) on the emissions of these gases (Ball, 2013). This understanding may link pore-scale micro-sites in which microbial activity occurs to larger gas exchange pathways, and can include the identification of ways to quantify effective parameter values that can be used to constrain these processes.

It is also important to better understand how small-scale dynamics in physical and hydraulic properties, preferential flow processes, and hot spots and moments affect larger scale (e.g., ecosystem-level) carbon, nutrient, and greenhouse gas cycling and fluxes. Soil structure is one important yet overlooked factor in hydrological processes relevant to earth surface models (Fatichi et al., 2020). Pore-scale dynamics affect landscape-scale gas exchange processes (Ebrahimi & Or, 2018), but may require more knowledge of how different soil pore domains affect gas diffusion and convection (Jayarathne et al., 2020; Kristensen et al., 2010). This information can be used to explore drivers of changing carbon cycles (Norby and Zak, 2011; Warren et al., 2021) and how greenhouse gas emissions respond to shifts in environmental conditions (e.g., drought, warming, elevated CO_2).

1.3. Dynamic changes in soil properties and influence on processes, including water retention, coupled heat and mass transfer processes (e.g., gasses, water)

Most theoretical and practical depictions of soils assume that their properties are constant through time. The reality, however, is that soil properties change over a range of timescales, from near-instantaneous shifts in volumes and bulk densities that can occur in non-rigid (i.e., swelling) soils (Stewart et al., 2016a; 2016b) to multi-year shifts in physical properties that can result from changes in soil management and corresponding effects on organic matter content, structure, etc. (Basset et al., 2023; Or and Ghezzehei, 2002). Water retention is a fundamental soil property that responds to changes in other dynamic soil properties, for example, pore size distribution (Della Vecchia et al., 2015; Leij et al., 2002). Many studies have identified positive correlations between soil organic matter content and soil water-holding capacity (Bagnall et al., 2022; Bordoloi et al., 2019), though some work has called into question that relationship (Minasny and McBratney, 2017).

Dynamic changes in the composition and structure of the soil matrix also influences environmental processes such as gas emissions and exchange, solute transport, and heat exchange. In terms of gas exchange, soil macropores and large inter-aggregate spaces can lead to faster gas diffusion (Jayarathne et al., 2020) and greater fluxes of greenhouse gasses such as carbon dioxide (McCourty et al., 2018). Cracks that form in soils can be conduits for carbon dioxide and water vapor exchange, as thermal convection causes warmer, moist air to rise from the cracks whenever the overlying atmosphere is relatively cool (Weisbrod et al., 2009; DeCarlo and Caylor, 2019). The presence of larger, structural pores can also reduce soil thermal conductivity in unsaturated soils, since larger pores tend to dewater earlier than small pores, leading to inverse relationships between aggregate size and heat transfer rates (Hamas, 1963; Usowicz et al., 2013). Linking thermal conductivity with water retention characteristics, which convey information about the amount of water-filled pore space within the soil, may be one avenue for better understanding of heat transfer processes in soils (Dong et al., 2015). More work is also needed to better understand and model coupled heat transfer and biogeochemically driven mass transport, including how these interactions translate from pore- or pedon-scales to larger field scales.

1.4. Surface energy balance and evapotranspiration

Evapotranspiration (ET) is a critical component of the hydrologic cycle that connects the water (evaporation), energy (latent heat flux), and carbon (transpiration-photosynthesis trade-off) cycles (Fisher et al., 2017). Globally, about 60% of the incoming terrestrial precipitation is returned to the atmosphere through evapotranspiration (Oki and Kanae, 2006). Accurate ET estimates and forecasts are crucial for numerous purposes including assessing climatic change and energy partitioning, designing and operating irrigation and water resource infrastructure, and accurate agroecosystem and hydrologic modeling. Multiple methods of estimating ET have been developed at various scales, including empirical methods (i.e., Penman-Monteith) and surface energy balance methods. Further, remote sensing-based estimates of ET are increasingly available at various spatial scales. Given the importance of ET in hydrologic cycle and in agricultural production, we will work to determine factors affecting ET at various spatial scales (i.e., field scale versus regional scale), quantify error associated with different estimation techniques, and improve methods of partitioning soil evaporation and plant transpiration.

1.5. Drivers of hydrologic change

Wildfires are increasing in frequency and severity across the United States, and particularly in the western region of the country. Warmer and drier weather patterns have extended and prolonged fire seasons, and the result has been a near-doubling from 1984-2015 forest fire-affected areas in the western U.S. (Abatzoglou and Williams, 2016). While much attention has focused on forested areas, wildfires have also increased in the grassland-dominated Great Plains by ~400% in recent decades (Donovan et al., 2017). Wildfires are strongly influenced by the moisture content of dead fuels, including fine dead fuels (i.e., litter) on the soil surface, and soil moisture observations can be used to improve grassland fuel load predictions (Krueger et al., 2022).

The adverse impacts of wildfires on watershed hydrology and soil erosion have been reported in numerous studies (e.g., DeBano, 2000; Benavides-Solorio and MacDonald, 2005; Robichaud et al., 2016). Soil water repellency is one effect that has been observed after fire in many ecosystems (DeBano and Letey, 1969; DeBano, 1981; Wallis and Horne, 1992; DeBano, 2000; Doerr et al., 2000; Doerr and Shakesby, 2012; Chen et al., 2018). Organic coatings on soil particles are a primary cause (Prescott and Piper, 1932; Woudt, 1959; Wallis & Horne, 1992; DeBano, 2000; Doerr et al., 2004; Huffman et al., 2001), and the degree and persistence of soil water repellency is influenced by vegetation type (Prescott & Piper 1932), soil organic matter amount and type (Capriel et al., 1995), soil particle size (Huffman et al., 2001), initial hydrophobic condition (Doerr et al., 2003; Huffman et al., 2001) and water content (MacDonald and Huffman, 2004; Huffman et al., 2001), oxygen availability during fire (Bryant et al., 2005; Savage et al., 1972), fire intensity (Doerr et al., 2003; Bryant et al., 2005), and fire duration (DeBano & Krammes, 1966).

Fire-induced hydrophobicity of surface soils and loss of vegetation cover often lead to increased runoff and sediment yield (DeBano et al., 1976; DeBano, 1981, 2000; Lewis et al., 2006). Indeed, most studies on post-fire hydrology and erosion have suggested elevated runoff and erosion rates for 1-2 years post-fire (Benavides-Solorio and MacDonald, 2005; Coelho et al., 2004). Persistent wildfire impacts on runoff and erosion due to drought and delay in plant regrowth, among other factors, have also been reported (Mayor et al., 2007). Nonetheless, we are currently limited in our ability to assess and predict soil hydrophobicity effects on post-fire infiltration and runoff at the watershed scale. Specifically, we need better information on (i) how hydrophobicity affects fire-induced infiltration compared to soil structure alterations, (ii) the geochemical nature of fire-induced hydrophobicity (Samburova et al. 2021), and (iii) how well existing and recent infiltration models (e.g., Green and Ampt, 1911; Abou Najm et al., 2021) perform under post-fire conditions.

1.6. Water, solute, and heat flow in heterogeneous systems

Soils are inherently heterogeneous, containing diverse features such as fissures, air pockets, stones, and roots in different horizons. This heterogeneity significantly influences water and heat movement, evident in phenomena like capillary barriers and water funneling caused by rock inclusions (Stormont and Anderson, 1999). Both horizontal and vertical variations in soil structures impact water flow dynamics, driven by unsaturated hydraulic conductivity and hydraulic head gradients. This complexity leads to rapid spatial and temporal variations in soil water flow, with implications for percolation, capillary rise, and soil chemical transport. The heterogeneity arises from factors like deposition, land use, and management practices, giving rise to distinct hydraulic properties, preferential flow pathways, and instabilities that affect water residence time in the soil.

Soil heat flux and moisture are crucial components of the surface energy balance and water budget (Yang et al., 2005). The surface heat flux constitutes approximately 20% of the available energy in grasslands and agricultural areas (Foken, 2008; Wang et al., 2010). Challenges arise in reproducing surface soil conditions in regions with significant vertical soil heterogeneity, as land surface models often rely on a single parameter set for soil hydraulic and thermal processes (Yang et al., 2005). Recent studies highlight the limitations of approximating vertically heterogeneous soils with homogeneous representations and emphasize the substantial impact of vertical heterogeneity on subsurface processes, soil wetness, and energy partitioning (Yang et al., 2005). Soil heat flux is computed using various methods, including net radiation residuals, sensible and latent heat fluxes, the Force-Restore method, and the diagnostic equation for soil temperature (Chen and Dudhia, 2001). Accurate measurements of soil heat flux are vital for validating models, guiding fieldwork designs, and addressing spatial heterogeneity in soil heat fluxes (Gao et al., 2017).

Characterizing water movement in the unsaturated zone is complex due to the nonlinear nature of Richardson-Richards equation and the challenge posed by soil spatial heterogeneity (Šimůnek, 2005; Feyen et al., 1998). Modeling approaches can be deterministic, simplifying heterogeneous soil into homogeneous representations or directly modeling its variability, or stochastic, treating soil hydraulic properties as random variables (Feyen et al., 1998). The streamtube or parallel column method, which assumes vertical flow within independent columns and integrates variability via probability density functions, is a prominent stochastic approach (Dagan and Bresler, 1983; Zhu and Mohanty, 2002a). Notably, pore-scale models, like those from Alaoui et al. (2011), simulate changes in soil properties due to compaction and shearing. However, soil heterogeneity can result in preferential flow, affecting soil water residence time and chemical transport (Šimůnek et al., 2003; Dekker and Ritsema, 1994). The suitability of Richards equation-based models is sometimes limited, lacking a comprehensive physical theory linking flow phenomena. Streamtube models, while insightful for 2D flows, need further exploration in 3D unsaturated conditions and under realistic flow regimes (Leij et al., 2006; Zhu et al., 2006; Ojha et al., 2017). Filipović et al. (2019) revealed that 1D dual-domain models can effectively represent soil heterogeneity, suggesting the need for future research on the interplay between hydraulic parameters to enhance modeling accuracy.

1.7. Deep vadose zone processes and linkages to groundwater

Deep vadose zone processes are pivotal in the hydrologic cycle, influencing water and energy fluxes, plant transpiration, and groundwater recharge rates (Twarakavi et al., 2008). Contaminant transport through this zone can pose significant environmental hazards (Simunek and van Genuchten, 2016). In regions with a substantial vadose zone thickness (>10 m), the lower section of the profile may operate differently from surface processes, impacting pollutant removal (Wellman et al., 2011) and soil-atmosphere interactions (Seneviratne et al., 2010). The deep vadose zone, situated below root zones or excavation depths, generally exhibits slower flow and transport rates for contaminants, and although less explored, it's crucial for understanding agriculture, crop growth, and soil water dynamics.

Quantifying groundwater recharge, especially in semi-arid areas with changing climate conditions, is crucial, and managed aquifer recharge (MAR) is emerging as a vital strategy, reliant on accurate simulation of variably saturated flow and transport in deep vadose zone, which remains challenging due to soil heterogeneity and limited hydraulic data (Perzan et al., 2023; Cockett et al., 2018; Meixner et al., 2016, Sasidharan, S.,2018a). Recent years have witnessed the development of physically-based integrated hydrologic models that couple surface water and groundwater processes through various schemes (Maxwell et al., 2014; Paniconi and Putti, 2015). These models, such as ParFlow and simplified formulations like the Unsaturated Zone Flow (UZF) package and the Integrated Water Flow Model (IWFM), offer effective computational methods to simulate complex hydrologic processes across various scales (Niswonger et al., 2006; Dogrul et al., 2012; Kollet and Maxwell, 2008).

However, due to logistical difficulties in sampling deep soils, little is currently known about their physical properties or the influence of those properties on water and solute transport, which is crucial for development of advanced models. Future work will seek to improve our measurement and estimations of deep soil physical properties with the goal of improving numerical simulations of water and solute transport within the deep vadose zone, including quantification of recharge and contamination. Additional areas of interest include artificial recharge, aquifer storage and recovery, and development of predictive models to estimate deep soil properties.

1.8. Behaviors of emerging contaminants in soils

Emerging contaminants represent different classes of novel chemistries used in agriculture, industry, and consumer products. Relevant categories include per- and polyfluoroalkyl substances (PFAS), pharmaceuticals and personal care products (PPCPs), hydraulic fracturing fluid additives (HFFAs), hydraulic fracturing flowback contaminants (HFFCs), engineered nanoparticles (ENPs), and micro- and nano-plastics. The PFAS chemicals in particular have garnered widespread attention as they have become widely detected in even pristine settings and their risks for human and ecosystem health become more apparent. The proliferation of antibiotic resistance genes (ARGs) and other biological pathogens also represent potential environmental pollutants that require additional investigation. Public concerns over these chemicals are rising, yet their prevalence, fate, and transport through the vadose zone remain poorly understood (Bell et al., 2019; Richardson and Kimura, 2017; Sauvé and Desrosiers, 2014). Of particular challenge, complex physico-chemical interactions that occur in the subsurface can cause each contaminant to have unique behaviors. Therefore, being able to generalize soil processes involving emerging contaminants is needed to properly manage their risks to ecosystems and the public, but making this advancement requires a much more fundamental grasp of the underlying mechanisms.

2. Apply soil physical and vadose zone concepts to improve soil and water management

2.1. Applications to address soil function and soil resiliency (including climate change mitigation)

Soil is one of the Earth's biggest carbon sinks (Lal, 2004). Soil organic carbon enhances aggregation, in return, soil aggregation can increase soil organic carbon storage by physically protecting carbon from mineralization by microbes through encapsulation it in smaller pores and by reducing soil erosion (Razafimbelo et al., 2008; Six et al., 2002). Soil organic carbon dynamics and aggregates (including stability and size distribution) interactions is thus clearly important for microbially driven biogeochemical processes (e.g., greenhouse gas emissions) and climate change mitigation (Blaud et al., 2012; Rillig et al., 2016; Vos et al., 2013; Wang et al., 2019). Macroaggregates have been suggested to play a fundamental role in the early stages of organic carbon protection as they represent a preferential site for the formation and the stabilization of carbon; however, microaggregates are thought to be of particular relevance for organic carbon storage due to their relative stability (Angers et al., 1997; Six et al., 2000). Soil aggregate size distribution and stability are thus important indicators of physical carbon stability, which plays a critical role in mitigating carbon emissions from the agricultural system to the atmosphere by lengthening the turnover time, increasing the capacity of soil to sequester carbon, and hence enriching soil carbon content (Six et al., 2002).

Improved soil organic carbon and aggregation also have the potential to enhance soil water conservation (Blanco-Canqui and Ruis, 2020). Due to climate change, the frequency, intensity, and duration of drought are projected to rise over most crop-producing areas in the United States and are expected to threaten crop production at regional to national scales (Zipper et al., 2016). Increasing soil organic carbon can enhance water holding capacity on soils with similar texture (Hudson, 1994; Minasny and McBratney, 2018) and improve water infiltration by supporting greater aggregate formation and, hence, a greater volume of pore spaces (Franzluebbers, 2002; Lado et al., 2004). Therefore, soils with higher organic carbon can retain more water under vapor pressure deficit, protecting crops from losses induced by drought (Carminati and Javaux, 2020; Iizumi and Wagai, 2019). Based on the U.S. National Soil Characterization Database, an increase in soil organic carbon by 1% would increase plant available water capacity by 0.6-1.7% (Libohova et al., 2018).

Agricultural management practices have important impacts on soil carbon storage and soil aggregates. Climate-smart agriculture practices (e.g., no-tillage, cover cropping) are essential strategies to address greenhouse gas emissions and improve soil drought resiliency in agroecosystems. However, the adoption of these practices on agricultural lands across the United States is widely considered inadequate and sporadic. The effectiveness of these climate-smart agriculture practices depends on environmental factors and management conditions. The high degree of uncertainty in the outcomes is a key limitation to adopting these management practices. Reducing uncertainty requires an improved understanding of the agronomic and environmental benefits of climate-smart agriculture practice in diverse cropping systems across the United States.

2.2. Address soil-related challenges within the water-food-energy-climate nexus

Climate change is leading to disparate impacts on water availability and crop production in different regions. Because of increasing plant water use and evaporation from soil combined with more variable rainfall caused by climate change, many areas globally may expect to see a decrease in agricultural productivity (Hussain et al. 2016; Schlenker and Roberts, 2009). Alternatively, other regions may see increases in productivity (Di Paola et al. 2018; Potopova et al. 2017; Gregory and Marshall, 2012). Prior work has indicated that yields of the world's three major crops– maize, wheat, and rice– are expected to decrease globally unless measures are taken to minimize climate change (Challinor et al. 2014). In the U.S., it has been predicted that corn, soybean, and cotton yields will be reduced by 30-82%, depending in the severity of future warming (Schlenker and Roberts, 2009) In addition to changes in water availability, expected changes to agricultural production due to climate change include increased pest pressure (Skendzic et al. 2021), increased occurrence of crop disease and frequency of outbreaks (Newberry et al. 2016; Velasquez et al. 2018), and increased heat stress for livestock (Lacetera 2018), among others.

2.3. Physics of growing media for food and nursery crop production on Earth and beyond

Fundamental concepts from soil physics can also be applied to better characterize and manage growing media for food and nursery crop production. For example, containerized nursery production is the main way by which many fruit, vegetable, and horticultural crops are grown.

Nursery containers typically use non-mineral substrates, including organic materials such as pine bark, wood fiber, peat, and coir from coconut husks, since these materials can avoid water-logging and disease issues. In general, nursery production requires proper management of water within individual pots to minimize shrinkage or crop loss and to ensure environmental and economic sustainability. Too much water can lead to root asphyxia, development of pathogens, or wasted agrichemicals due to leaching; too little water causes reduced growth and time to market due to plant physiological stress (Kerloch and Michel, 2015). Therefore, having adequate understanding of the physical and hydraulic properties of soilless substrates is necessary in order to form best management practices for irrigation (Fields et al., 2020). This information is particularly important because water movement and retention in bark, peat, and other substrates are affected by the moisture content and infiltration patterns (Hoskins et al., 2014). At the same time, soilless growing media exhibit hysteretic behavior during wetting and crying cycles (Naasz et al., 2005; Raviv et al., 2019). Several specific mechanisms influence this hysteretic behavior, including non-geometrical uniformity of the pores, trapped air within the substrate, and water repellency (Naasz et al., 2008). These factors are all related to pore characteristics, making it critical to have suitable methods to quantify and understand how pore structure and size distributions influence water retention, water availability to plants, and water movement through soilless substrates.

Growing crops and other plants in space is another area where soil physics concepts can be refined and better understood. Water distributions in porous media change under microgravity conditions, such as on the International Space Station or in a transit vehicle to the moon or Mars. These differences can lead to decreased oxygen diffusion rates and development of root zone hypoxia (Heinse et al., 2015). Rearrangement of individual particles and formation of intra-pore air bubbles also act to reduce hydraulic conductivity under microgravity conditions (Bingham et al., 2000). Improved water supply and resource recovery concepts are needed for reduced gravity environments where complications of reduced gravity on system components continue to present challenges (e.g., plant stress, non-optimal root environment) for highly successful outcomes. These factors can act as impediments to future human exploration of space and nearby celestial bodies. Calls for in situ resource utilization on the Earth's moon and Mars will likely include use of clay, silt, sand, and larger-sized particles that could be utilized for larger-scale crop production, but at reduced gravity levels. The consequences of reduced gravity for growing plants in these surface materials are yet to be understood and tested.

2.4. Applying soil physics to assess or improve soil health

Soil health refers to the sustainable capacity of soil to perform agronomic and environmental functions (e.g., agricultural productivity, response to management and inputs, resistance to biotic and abiotic stresses) (Lal, 2011). Healthy soil is therefore the cornerstone of agricultural production.

Soil health represents the ability of soil to function as a biodiverse organism that sustains terrestrial life, recognizing that soil contains biological elements that are key to agroecosystem services (Jian et al., 2020). The addition of an urgently needed biological perspective to soil management in order to address longer-term sustainability challenges for crop production is therefore one of the most important achievements of the soil health framework (Bünemann et al., 2018). Soil health research tends to bias toward a biology/microbiology emphasis; however, soil health is not all biology/microbiology (Coyne et al., 2022). Having an excessively narrow focus on the importance of soil biology/microbiology neglects important physical and chemical interactions in soil that are crucial to soil functions.

Soil physical environment provides information related to mass and energy transport through the soil, as well as conditions affecting microbial community activity, crop growth and erosion processes (Allen et al., 2011). Soil structure, which describes the spatial arrangement of particles to complex aggregations forming pores and channels, is the most important soil physical characteristic (Bronick and Lal, 2005). Soil microbiome and microbes mediated biogeochemical processes (e.g., nutrients cycling, greenhouse gas emissions) is intricately linked with soil structure, such as aggregation and pore configuration, as this structure provides microhabitat for microorganisms and regulates the fluxes of water, oxygen and nutrients through the system influencing microsite habitability (Wang et al., 2019; Hartmann and Six, 2023). Soil physical structure is therefore essential for soil to perform ecological functions.

Despite the impressive achievements in the field of soil biology/microbiology, relying solely on this approach will not yield the desired level of effectiveness in enhancing soil health. To make substantial contributions to soil health improvement, it is crucial to integrate this approach more closely with an understanding of the surrounding physical environment. Additional research on investigating the influences of agronomic practices on soil services from soil physics perspective, developing physical indices to assess or monitor soil processes, and optimizing management practices associated with soil physical health improvement are important for enhancing agroecosystem sustainability and productivity (Talukder et al., 2023). Land fallowing is sometimes needed to manage scarce water resources, data are lacking on how to maintain soil health under these conditions. Soil properties can be modified to maintain or enhance soil health using amendments. By appreciating the physical environment as a foundation for soil health, we believe better recommendations can be made to assist the producers' community in its stewardship of soil as a critical natural resource.

2.5. Soil moisture and other soil sensing networks and their applications

Recent advances in *in situ* soil moisture sensing technologies and expanded support for soil moisture monitoring have facilitated a growth in soil moisture networks at local, state, and national scales (Ochsner et al., 2013; Cosh et al., 2021). These networks utilize a variety of sensor types, sensing depths, and data processing procedures and various purposes and stakeholders. The rapid expansion of soil moisture sensing, coupled with a lack of unified community structure or guidelines, has resulted in many disparate monitoring networks and non-harmonized datasets that are difficult to employ in practice. Related efforts include those of the National Coordinated Soil Moisture Monitoring Network (NCSMMN), a community effort whose creation was mandated by Congress. Future work carried out by this group will include developing standards of data quality processing and metadata reporting, methods of unifying data from disparate networks and sensor types, and applying data from these networks for critical applications including drought monitoring and prediction, wildfire prediction, streamflow forecasting, flood prediction, and others.

The NCSMMN provides a tremendous opportunity to validate to some degree remotely sensed soil moisture from satellites as well as to update and validate modeled soil moisture from land surface- and other hydrological-models. However, the vast majority of land across the US and abroad has no direct in situ measurements of soil moisture and the remotely sensed estimates are generally limited to surface and near-surface reflection-based approximations, which may or may not be well-correlated to subsurface moisture. Application of machine- and deep-learning resources have the potential to provide much improved connections to subsurface properties from surface signatures and especially from subsurface measurements of soil moisture, i.e. from a single sensor, the entire soil moisture profile can be estimated (Ghorbani et al., 2021; Sadeghi et al., 2020) and estimates of groundwater interactions with the vadose zone are also possible (Sadeghi et al., 2022).

2.6. Proximal and large-scale soil moisture sensing technologies

Recent advancements in proximal and remote sensing technologies have greatly enhanced our ability to monitor soil moisture dynamics from local to global scales. Proximal sensing techniques, such as electromagnetic induction (EMI), cosmic-ray neutron probes (CRNP), and ground-penetrating radar (GPR), have shown promise in providing high-resolution and real-time soil moisture information. For instance, EMI sensors can capture soil moisture spatial variability by measuring changes in electrical conductivity (Robinson et al., 2012; Huang et al., 2017), while CRNP instruments utilize the interaction between epithermal neutrons and hydrogen atoms to estimate soil moisture content over field- and ecosystem-level footprints (Zreda et al., 2012; Andreasen et al., 2017). On the other hand, GPR offers the potential for mapping soil moisture patterns with high spatial resolution (Huisman et al., 2003; Weihermüller et al., 2007). These proximal sensing approaches have significantly advanced our understanding of soil moisture dynamics and its interactions with vegetation and hydrological processes.

In the realm of remote sensing, there have been notable advancements in utilizing passive and active microwave sensors, such as radiometers and synthetic aperture radar (SAR), for soil moisture estimation. Passive microwave sensors leverage the sensitivity of microwave radiation to soil moisture, allowing for large-scale monitoring of soil moisture over vegetated areas. The availability of satellite-based sensors, such as the Soil Moisture Ocean Salinity (SMOS) (Kerr et al., 2012) and Soil Moisture Active Passive (SMAP) (Entekhabi et al., 2010) missions, has provided global coverage of soil moisture at various spatial and temporal scales. Active microwave sensors, like SAR, offer the advantage of high-resolution and all-weather capabilities, allowing for detailed mapping of soil moisture patterns. Furthermore, the integration of remote sensing data with advanced data assimilation techniques and modeling approaches has facilitated improved spatiotemporal mapping and forecasting of soil moisture conditions.

Further developments in proximal sensing techniques should focus on enhancing their portability, affordability, and ease of use for widespread adoption in agricultural and environmental applications. Additionally, efforts should be directed towards improving the accuracy and reliability of remote sensing approaches by addressing challenges such as vegetation interference, surface roughness effects, and the need for higher spatial resolution observations. Integration of multiple sensing platforms and data fusion techniques can also help to improve the overall accuracy and robustness of soil moisture estimation One example is the OPtical TRApezoid Model (OPTRAM) (Sadeghi et al., 2017), which is based on the physical relationship between surface soil moisture and shortwave infrared transformed reflectance (STR) that leverages high-resolution (i.e., 20-30 m pixels) remote sensing from Sentinel 2 and Landsat 8 observations that can reveal heterogeneous soil moisture patterns. However, methods based on remote sensing observation are typically limited to study the soil skin's layer and more comprehensive approaches are necessary to monitor rootzone conditions and improve our understanding of soil-plant-atmosphere interactions.

3. Develop new instrumentation, methodology, and models to characterize and interpret soil physical and vadose zone processes

3.1. Sensor development

Information about the soil and vadose zone properties is important as it controls soil water, heat, solute, and gas fluxes and helps understand the interactions between soil, environment and human activities (Fatichi et al., 2020; Novick et al., 2022). Over the past decades, research effort has focused on the development of soil sensors that can be deployed in the laboratory and field conditions to measure and estimate soil water, heat, solute, and gas concentrations and fluxes in the real-time (Robinson et al., 2008; Tuli et al., 2009; Fan et al., 2022). Advances in sensing technologies enable characterization of soil physical and vadose zone properties and processes from the pore size scale to field scale (Quiring et al., 2016).

As soil sensor measurements become more accessible, researchers have started to develop dual-/multi-purpose sensors that can simultaneously measure multiple soil properties and fluxes. Examples include thermo-time domain reflectometry (thermo-TDR) (Ren et al., 2003), TDR-EC probes (De Carlo et al., 2021), and soil moisture-nitrate probes (Yin et al., 2021; Zhu et al., 2021). There are also an increasing number of studies that attempt to retrieve multiple soil physical properties and fluxes from the coupled sensor measurements such as using the thermo-TDR to measure soil water content, thermal properties, bulk density, porosity, and air-filled porosity (Peng et al., 2019). Sensor companies and researchers are currently developing capabilities that include machine-learning of data from sensors that may lead to information on other soil properties such as soil texture, surface area, bound water, and other information continued within the sensor signal.

Future research is needed to make use of the measurements from existing sensors and develop new multifunctional, chemical, and biological sensors for sensing soil physical, chemical, and biological, properties that either cannot be measured or are difficult to measure (e.g., NO_3^-, O_2, CO_2, CH_4, NH_3, N_2O, antibiotics) at local (plot to field) and landscape scales to monitor and understand soil functions (e.g., soil health), soil-organism interactions (e.g., pore structure), and changes in properties (e.g., aggregates). Particularly, sensors that will be placed in the ground should be placed with minimal disturbance (e.g., reducing the preferential flows), be environmentally benign, and have minimal impact on land use and land management (e.g., irrigation, fertilization, tillage).

3.2. Sensor protocols and evaluation/inter-comparison

Accurate measurement and monitoring of state variables (e.g., soil water storage, heat storage, solute concentration) and fluxes (e.g., drainage, evaporation, thermal and solute diffusion, soil respiration) are essential for understanding and managing vadose zone processes. However, with the development of new sensors with different designs, principles, and characteristics, the reliability and comparability of sensor measurements heavily depend on the calibration and installation procedures. By developing installation and maintenance standards, establishing community-approved data quality and metadata guidelines, and deploying inter-comparison sensor testbeds, researchers can ensure that measurements are accurate, consistent, and comparable across different studies and locations to maximize the utility of data resulting from these sensors. Sensor inter-comparison testbeds provide a controlled environment for evaluating and comparing the performance of various sensors under standardized conditions (Cosh et al., 2016) and for developing upscaling methods (Brown et al., 2023). By subjecting sensors to identical environmental conditions and monitoring their response, researchers can assess their accuracy, precision, reliability, and other performance metrics. This facilitates the identification of sensor strengths, weaknesses, and limitations, aiding researchers and practitioners in making informed decisions regarding sensor selection for specific applications. Furthermore, the establishment of sensor inter-comparison testbeds promotes transparency and collaboration within the scientific community, fostering the exchange of knowledge, best practices, and advancements in sensor technology for vadose hydrology and agriculture.

3.3. Model-data fusion and integration for decision-support systems (including AI and robotics/IOT)

With the advances in soil sensor networks (e.g., Ochsner et al., 2013; Cosh et al., 2021), observations of soil properties such as soil moisture, temperature, and gas emissions are available across large spatial extents and over long periods. Soil is a heterogeneous system and the relationships between soil properties and processes and sensor measurements are often non-linear and location-specific. Process-based models are well developed that can be used to characterize soil water, heat, nutrient and gas fluxes at the point to field scales, but it remains a challenge to parameterize these models across large regions. To address these problems, Artificial Intelligence (AI) and Machine Learning (ML) algorithms have been developed and applied to model and map soil properties (moisture, temperature, CO_2 fluxes) and processes using the sensor measurements collected from point to global scales (Abbaszadeh et al., 2019; Guevara and Vargas, 2019; Alizamir et al., 2020; Hamrani et al., 2020; Huang et al., 2020). Furthermore, the observations of soil sensors can be combined with process-based models via a data assimilation framework (e.g., Kalman filter) to provide forecasts of soil variables over time and across large regions (Vergopolan et al., 2021).

The use of AI and ML can provide fast estimation of soil properties and processes given the availability of sensor observations but most of the data-driven models are location-specific and difficult to interpret. There is an urgent need to achieve a better understanding of these "black-box" models and develop physics-informed AI/ML framework that can integrate soil and vadose zone processes into the AI/ML models (Li et al., 2022). There is also a need to transform the sensor observations into actionable information with the control systems (e.g., robotics) to improve agricultural and natural resources management and decision-making such as irrigation, fertilization, and pest control (Huang, C.H. et al., 2021; Huang and Chen, 2023; Sharma et al., 2023).

3.4. Development and parameterization of process-based models that simulate soil and vadose zone processes

Process-based physical models enjoy a long history in the soil physics community, as embodied by the long history of multi-state research collaborations supported by USDA and other agencies. The HYDRUS software, which is based on the numerical simulation of the Richardson-Richards equation for water movement and storage, has long been one of the most commonly used approaches to solve many fundamental research questions related to soil physics and hydrology (Šimůnek and van Genuchten, 2008). Over the years, the software has become integrated with many other physical models, including solute advection-dispersion, heat transfer, CO2 diffusion, and water vapor transport (Šimůnek et al., 2016), and most recently has been adapted to simulate stable water isotope dynamics under non-equilibrium conditions (Zhou et al., 2021). However, several challenges have emerged related to this process-based modeling work, including uncertainties related to parameterization, scale, and non-uniform and heterogeneous processes.

Most models based on the Richardson-Richards equation, including the HYDRUS family of models, assume that soil properties can be described using one or more sets of effective hydraulic parameters. These applications typically consider soil to be a single entity, though more sophisticated conceptualizations divide the soil into matrix versus fracture domains (e.g., Gerke et al., 1993; Stewart, 2019; Zhang et al., 2019, Yang et al., 2022). Others have argued, however, that the Richardson-Richards equation is not the best conceptual model for water movement under real-world conditions (Beven, 2018). Alternative approaches include kinematic wave depictions (Alaoui et al., 2003) and viscous flow (Germann and Karlen, 2016). Beyond the obvious differences in underlying perceptual models that exist for each of these types of models, each includes a set of parameters that can be difficult to uniquely constrain. The issues of parameter uncertainty typically increase along with model sophistication, leading to approaches such as Bayesian statistics to optimize parameter values (Jana et al., 2012; Schübl et al., 2022). At the same time, the parameters used in HYDRUS and similar models are generally identified or calibrated at 1-2 discrete scales, yet the physical depictions embodied by these parameterizations do not translate to smaller (e.g., pore-) or larger (e.g., hillslope- or watershed-) scales. Altogether, more work is needed to 1) refine existing models to have greater capabilities, 2) develop better approaches for model parameterization, and 3) identify robust approaches to up- and down-scale depictions of physical processes that are included in these models.

Additionally, research efforts are needed to leverage the existing large-scale non-spatial and spatial soil datasets and models to build open-access APIs and website tools for researchers and land managers to use, process, and manage soil data and predict soil properties and functions. For instance, ongoing research is conducted to translate the existing pedo-transfer functions for soil hydraulic properties to open-access webtools (e.g., Handbook 60++) or scripts (Rosetta3 - Zhang and Schaap, 2017) so that the models can be applied easily in different disciplines and compared with other models widely used in agricultural systems, hydrology, ecology, and climate science.

3.5. Upscaling and downscaling of in situ, proximal, and remote sensing data

The upscaling and downscaling of soil physical properties and processes play a crucial role in understanding the complex and heterogeneous dynamics of the vadose zone. Accurately characterizing soil properties and processes across different spatial and temporal scales is essential for parameterizing models and devising effective management strategies, particularly in regions that lack extensive monitoring networks and with scarce soil geodatabases. Upscaling involves the extrapolation of small-scale measurements or observations to larger scales, enabling a broader understanding of soil behavior and its impact on hydrological and agricultural processes (Vereecken et al., 2007). Upscaling techniques integrate data from in situ, proximal, and remote sensing variables to derive representative values and parameters for larger spatial extents or longer time periods (Crow et al., 2012). By capturing the variability and interactions of different soil physical properties and processes, upscaling enables the development of robust models and management strategies that account for the heterogeneous nature of biophysical processes in the vadose zone.

Downscaling involves the refinement of soil information and process from larger to finer scales and allows for the estimation of local properties and processes based on information obtained from coarser-scale measurements or models. Downscaling techniques typically include regression models, machine learning models, or physically-based models in combination with available high-spatial resolution datasets like elevation, topographic indices, vegetation indices, or soil physical properties (Peng et al., 2017; Fang et al., 2018; Xu et al., 2022). In the vadose zone, downscaling involves integrating data from remote sensing platforms, such as satellite or aerial imagery, with in situ and proximal sensing measurements to derive detailed soil information at smaller spatial scales (Montzka et al., 2018; Abbaszadeh et al., 2019, Reyes et al., 2018). This enables the identification of spatial patterns, heterogeneity, and variability in soil properties and processes, facilitating targeted management practices and precise decision-making in agricultural and hydrological applications. The combination of in situ, proximal, and remote sensing variables in both upscaling and downscaling approaches offers a comprehensive framework for characterizing and understanding the vadose zone dynamics across a range of spatial and temporal scales. Future research in this area includes the development of new model-data fusion approaches aimed at blending a wide range of datasets, uncertainty quantification and propagation.

3.6. Geophysical tools to better quantify subsurface heterogeneity, hydrologically relevant properties, and groundwater and vadose zone interactions

Soil physical and hydraulic properties can be indirectly derived from geophysical measurements based on relationships with soil water content, salinity, and porosity, such as dielectric permittivity and electrical conductivity/resistivity (Scholer et al., 2011). Specifically, geophysical data can be either integrated with a physical hydrological model to yield hydraulic estimates following an inversion procedure (e.g., Camporese et al., 2011; Jaumann and Roth, 2018; Yu et al., 2022), or used as the input parameters of pedotransfer functions for the prediction of hydraulic properties (e.g., Wendroth et al., 2006; Casa et al., 2013; Mohanty, 2013).

Ground penetrating radar (GPR) and electromagnetic induction (EMI) are two widely used devices of non-invasive geophysical instruments that can be integrated into a mobile sensing platform to obtain geophysical properties of the soil and vadose zone in a time-effective manner. However, these instruments are often unable to capture the temporal variations of soil and vadose properties (e.g., water content, freeze-thaw) unless deployed on repeated surveys across the study field (Huang et al., 2017). By comparison, electrical resistivity tomography (ERT) deploys electrodes to the ground surface to monitor the changes in geophysical properties (e.g., soil moisture, solute) along a cross-section (2-Dimensional) or across an area (3-Dimensional) over time and inversely retrieves the soil physical and hydraulic properties over time (Michot et al., 2003; Koestel et al., 2008; Klotzsche et al., 2018).

In addition, the deep vadose zone's complexity, crucial for MAR systems and groundwater quality and quantity management, is traditionally gauged using small-scale soil samples, but emerging geophysical methods offer a promising avenue to address its large-scale heterogeneity and the challenges of upscaling. Techniques like airborne or towed Transient Electromagnetic (TEM), ERT, and borehole electromagnetic data have been instrumental. Specifically, they help in characterizing large-scale subsurface hydraulic properties (Kang et al., 2022) and are invaluable for MAR systems, aiding in the identification of optimal recharge locations and accurate estimation of recharge rates. These advancements underscore the significance of geophysics in demystifying the complexities of the deep vadose zone's heterogeneity.

Future research is needed to combine the geophysical measurements with other soil sensors or process-based/data-driven models to model and monitor the soil moisture dynamics and beyond, including heat, nutrient, and gas fluxes and reduce the non-uniqueness problems of the inversion. Research is also needed to model the soil-plant-atmosphere continuum and extend the measurements from soil physical and hydraulic properties to chemical and biological properties and functions.

3.7. Integration of sensor data, remote sensing data, in situ measurements across scales into scale-appropriate data analysis, modeling, and decision-support tools

Soil sensing, in-situ measurements, and remote sensing of soil moisture, soil water tension, salinity, solutes, gasses, or non-aqueous fluids in soils/vadose zones span a wide range of methods and are employed over a wide range of applications. Each method generates data that are linked to a measurement support scale that is intrinsic to each specific method, e.g., the moisture content of a neutron probe reflects the soil moisture within less than 1 m^3 of soil volume, immediately surrounding the neutron probe at the time of sampling, cosmic ray neutron sensing (CRNS) has a support volume that spans a circle of 200 m, moisture-dependent depth into the top soil with distance-based influence of soil moisture within that footprint on the measured datum. Many remote sensing data have lateral resolution of 10 to 1000s of square meters per pixel and represent varying depths of the upper soil volume. The source area of monitoring wells in first encountered groundwater (immediately below the vadose zone) depends on the screen length, saturated hydraulic conductivity of the aquifer, hydraulic gradient, recharge and their spatial distribution. Measurement data are also associated with a representative temporal resolution, from less then one second (e.g., TDR measurement of soil moisture), to hour, day, month, season, or year (e.g., farm-scale or field scale nutrient mass balance).

Similarly, different applications require knowledge of soil/vadose zone status (moisture, tension, nutrient content, pollutant concentration, etc.) at various spatial and temporal scales of interest. For efficient nutrient management, resolution of the spatial distribution of soil nutrition needs are a function of nutrient application methods and range from less than 10 m in precision agriculture, at daily or weekly intervals, to field scale at seasonal or annual intervals. For contamination of groundwater, the source area of a domestic, public, or irrigation well, or the source area of baseflow to a stream segment is a spatial unit (scale) of significant interest, which may range from few tens to thousands of meters in length. The mixing of vadose zone recharge to groundwater in wells and stream baseflow reflects water ages that span hours to decades or centuries.

Hence, measurement support volumes and soil/vadose zone volumes of interest to a decision-maker (e.g., farmer, consultant, public water supplier, regulatory agency) are different and require upscaling, downscaling, and integration of data across scales. Data analytical methods and models have their own spatio-temporal resolution. Data processing that is appropriate given measurement support volume, model resolution, and scale of interest to decision-makers/users is critical, yet limited guidance is available for the many types of measurements collected in association with understanding and managing soil and vadose zone processes. We use existing and new field sites with multiple/redundant measurement systems across the groundwater-vadose zone-soil-plant-atmosphere continuum, and a range of data analysis (statistical data analysis, artificial intelligence) and modeling (e.g., HYDRUS, SWAT) to develop guidance and better understanding of data processing and modeling protocols for specific decision-support system that are appropriate to measurement support scale, model resolution, and decision-maker/user scale of interest..

4. Translate new concepts and methods to students, stakeholders, and the public

4.1. Making our science more actionable for stakeholders and decision makers through knowledge translation, extension, and public outreach

Soils provide essential ecosystem services to our society, such as supporting the production of food, fiber, and fuels, cycling of water and nutrients, mitigating climate change, maintaining biodiversity, and regulating water quality and quantity (Baveye et al., 2016; Pereira et al., 2018). Human behavior, perceptions, governance, and decision-making impact soil both positively and negatively (Richter et al., 2015; Vanwalleghem et al., 2017; Geisen et al., 2019; Owens, 2020) and research on natural and anthropogenic disturbance on changes in soil properties (e.g., soil structure, compaction) and processes (e.g., erosion) is important for designing best management practices to sustain the soil resources.

Research has been conducted to evaluate the effects of natural (e.g., drought, flood, wildfire) and anthropogenic (e.g., tillage, cover cropping) factors on soil properties (often known as dynamic soil properties) and processes (Sullivan et al., 2022). There is a need to translate the new concepts and methods of soil and environmental physics to stakeholders and the public to better understand complex people-soil dynamics through partnerships between soil scientists and social scientists. Specifically, there is a lack of studies on using soil knowledge for human decision making about the land-use/land-management change and understanding how soil data is understood, interpreted, and acted upon by diverse land managers.

In addition, engagement with local, regional, state, and federal policy- and decision-makers and planning/regulatory agency personnel, with community-based organizations, and with volunteering committees can play a pivotal role in making science more actionable for stakeholders and decision makers. By deeply understanding the nuances of local issues, these groups can tailor scientific information to address pressing community concerns, fostering collaboration and trust. The Universities and Ag-Experiment Stations at land grant universities can act as bridges, connecting scientific research with on-the-ground site-specific and local challenges. They can catalyze co-created solutions, ensuring that both scientific insights, local knowledge, and socio-economic dynamics are harnessed to address the multifaceted social and scientific problems surrounding complex challenges such as remediation of contaminated water resources, protection of surface water and groundwater quality, sustainable groundwater management, climate change adaptation, habitat restoration, and community resilience against natural disasters.

4.2. Open-access and reproducible science

There is increasing research for open and scalable community-driven cyberinfrastructure (CI) to support innovative scientific inquiry based on software and data that are findable, accessible, interoperable, reusable, provenance traceable, and sustainable. There is a need for education and community development in software and data CI in soil and vadose zone research, education, and outreach activities, which are capable of real- and near-real-time archiving and manipulation of sensor and other field-based data, "leverage through sharing" of existing investments in university, federal, and commercial computing and infrastructure, engage community models for the assimilation and use of data for initialization, state estimation, or sensitivity analysis, and encourage the development or reuse of computational techniques to stimulate data enabled science through enhanced large-scale simulations and analysis of large volumes of data, streamline findability and accessibility of high-quality data, visualization tools, and modeling and analysis codes to help scientists and educators maximize the value of soil and environmental data and to generate transparent and reproducible research outcomes, and enable engagement with people and communities historically underrepresented.

4.3. Open-access educational resources

While open educational resources (e.g., online textbooks, laboratory exercises, etc.) have increased in popularity, especially since the onset of the COVID-19 pandemic, few such resources currently exist in the soil, environmental, and agronomic sciences. Such resources increase dissemination of scientific content, reduce redundancy in educational resource creation, and decrease the financial impacts of education on students. We welcome the sharing of existing or upcoming open educational resources within and outside the project group, which represents the majority of environmental soil physicists currently teaching in the U.S.

4.4. Improved pedagogy (teaching) methods

Research shows that certain teaching methods, including hands-on activities and group discussions, improve student learning and retention while also increasing student satisfaction (Davidson and Palermo, 2015). While some of these practices have been implemented in soil physics courses, in many cases teaching continues to rely on the traditional lecture-style dissemination of information, which relies heavily on student memorization and recitation of factual content rather than application of knowledge. We welcome the contributions of colleagues who seek to develop and implement new, interactive soil physics teaching methods, especially for the purpose of encouraging the wider use of those methods at other institutions.

4.5. K-12 outreach and education

Recent efforts by members of the Soil Science Society of America (SSSA) K-12 committee include developing and extending soil science-based lessons and activities to K-12 teachers with the goal of introducing students to these concepts at an early age. Research shows that developing children and young adults' interest in a subject at an early age informs their choice of that subject as a career path in the future (Sonnert et al., 2007; Wolbrecht and Campbell, 2007). Prior teacher inservice training events have proven successful, with teachers indicating that both their understanding of soil science topics as well as their comfort in teaching soil science in their classrooms have increased as a result of these trainings (Wyatt et al., 2022). Future similar trainings held in the future are expected to further increase the visibility of soil science among K-12 teachers and students who may, in turn, be more likely to choose this field of study in the future.

4.6. Diversity, equity, and inclusion and improving recruitment, retention of students in soil physics, hydrology, and environmental sciences

Presently, soil science is one of the least racially diverse fields within STEM (Berhe and Ghezzehei, 2020), and soil physics is the least gender diverse of all soil science subdisciplines in the U.S. (Vaughan et al., 2019). Many efforts are ongoing with the purpose of increasing recruitment, retention, and representation in the field, including the work of the ASA-CSSA-SSSA Diversity Equity and Inclusion (DEI) committee. Similarly, funding for the development of programs and initiatives to increase representation in the sciences has become a major emphasis of multiple federal and state funding agencies. We welcome the sharing of project members' experiences and findings of projects in this area.

4.7 Improving interdisciplinary interactions (see Hopmans 2020)

In recent years, the field of soil physics and hydrology has become increasingly inter- and trans-disciplinary (Hopmans, 2020). This presents unique opportunities for research in our field to address a growing number of societal issues including food and water availability and sustainability, as well as increase the impact of interdisciplinary research on policy and decision-making. Some examples of recent inter-disciplinary works include evaluations of soil water status on microbiological activity and greenhouse gas emissions (Bond-Lamberty et al., 2016), crop production and genetics (Azardbad, 2020) While challenges exist in bridging disciplinary boundaries, there remains strong potential to increase the efficacy of soil physics and hydrology-related research by improving our collaborations with scientists in relevant fields. Thus, in this proposal we encourage the development of new and continuation of existing inter- and trans-disciplinary research.

Methods for each sub-objective (states to add their information)

Objectives:

1. **Improve fundamental understanding of soil physical and vadose zone processes. (Fundamental understanding)**

   1.1. Improve understanding of preferential flow and its role in biogeochemistry

   - OR, VA: use isotope tracers in mobile/immobile domains, electrical resistivity tomography and transient electromagnetic method to detect preferential flow
   - DE: conduct column experiments to link soil structure with water flow and distribution and with biogeochemical processes (e.g., C dynamics, enzyme activities)
   - DE: perform water isotope analysis of field samples from a coastal wetland to improve understanding of vadose processes influenced by tidal events, storms and seawater intrusion.
   - TX: detect and predict preferential flow using *in situ* soil moisture sensors
   - CA: quantify impact of preferential flow on soil health and its dynamics under different shade/light treatments
   - CA, OR: perform tracer experiments and monitor nitrate, EC and oxyanion concentrations in the vadose zone and compare to vadose zone models that represent preferential flow
   - UT, MN, VA, CA, TX: develop novel models/algorithms for describing preferential flow in soil
   - MN, NV, CA, VA: improve understanding of infiltration behavior in water-repellent soils, and thereby improve understanding of preferential flow in water-repellent soils.

1.2. Study the role of soils in greenhouse gas emissions

- TX/LA/VA: evaluate GHG emissions under different pasture and row cropping management practices
- MT: measure carbon sequestration potential and greenhouse gas implications of bioenergy grass production
- AL: evaluate the effects of biochar and biopolymers on soil thermal and physical properties
- CA: monitor CO_2 and N_2O emissions and N cycling from agricultural fields flooded for groundwater recharge
- MN: quantify methane emissions from peatland soils by field measurements and modeling.

1.3. Dynamic changes in soil properties and influence on processes, including water retention, coupled heat and mass transfer processes (e.g., solutes, gasses, water)

- AL, VA: quantify variation of in-situ soil hydraulic properties in space and time under different land uses.
- AL: evaluate the effects of biopolymers on soil hydraulic properties.
- AL: evaluate water retention and hysteresis in two highly weathered soils and poultry litter
- IA/NC: characterize soil structure information from transport properties
- DE: measure effects of flooding and salinity on soil physical and hydraulic properties
- CA: evaluate impact of microclimate and different light/shade treatments on soil dynamics and the changes/evolution of soil properties
- CA: evaluate impact of intentional flooding of agricultural soils for groundwater recharge on physical soil clogging and infiltration rate
- WA, CT: evaluate the effects of emerging pollutants, including micro- and nanoplastics, on soil properties
- NM: evaluate the effect of land fallowing and addition of rock dust as amendments
- OR: dynamics of temperature, water flow, and in situ solute transport during drywell-recharge
- OR: understand change in hydraulic properties, in situ clay mobilization and clogging during various vadose zone MAR.
- KS: evaluate and measure *in situ* soil water retention curves

1.4. Surface energy balance and evapotranspiration

- CA: compare performance of micrometeorological and isotopic methods for evapotranspiration partitioning
- CA: estimate plant response to different light treatments
- AL: investigate microclimate conditions inside and outside of agroforestry systems
- DE: improve understanding of evaporation and evapotranspiration processes from soil under the influence of salt
- AZ: develop new means for estimation of crop water consumption from remotely sensed SWIR reflectance to conserve agricultural water resources.
- KS: Test new low-cost sensors for measuring field-scale evapotranspiration

1.5. Drivers of hydrologic change

- DE: establish and instrument a long-term monitoring site at the St. Jones Reserve to observe the changes in soil biogeochemical and hydrological processes under the influence of coastal flooding and seawater intrusion.
- NV: measure fire-impacts on soil structure, and measure sorptivity of sub-critically water-repellent soil in the field.
- AZ: fire-impacts on soil hydraulic properties and biogeochemistry, and time-scale of soil recovery
- CA: Assessing drought impacts on streamflow and groundwater resources across the US
- CA: Assessing the potential impact of managed aquifer recharge on streamflow and groundwater
- MT: analysis of woody plant expansion (WPE) and effects of prescribed fire in the Northern Great Plains
- WA,CT: quantify changes in soil hydrology induced by agricultural plastic mulch films
- KS: measure soil moisture at the watershed level using in situ, proximal and remote sensors to better understand the link between soil moisture and streamflow.

1.6. Water, solutes, and heat flow in heterogeneous systems

- LA: quantify spatial variability of soil properties and their influences on field-scale soil water dynamics and crop growth.
- VA: identify causes of tree mortality from growing media
- OR: use water and heat flow as tracers for recharge from drywell-MAR.
- CA: identify field/orchard-scale water, nitrogen, and salt fluxes in irrigated agriculture, through highly heterogeneous alluvial soil and vadose zone systems into groundwater.
- CA: perform basin-scale assessment of nutrient and salt management practices on nitrate and salt fluxes into groundwater.

1.7. Deep vadose zone processes and linkages to groundwater

- OR: explain complex deep vadose zone hydrology and subsurface heterogeneity on infiltration, recharge, and contaminant transport from drywell-MAR.
- CA: improve mountain system recharge prediction in the Sierra Nevada mountains.
- CA: assess the role of spatial variability in subsurface geological and geochemical heterogeneity on groundwater recharge and solute/contaminant transport.
- CA: examine nitrogen and carbon cycling processes and mobilization of heavy metals in the deep vadose zone.
- CA, OR: perform water quality threats assessment of drywells as stormwater drainage and aquifer recharge tools.
- NM: perform transient storage model parameter optimization using the simulated annealing method.
- AZ: build release database of Maricopa Deep Infiltration Site experimental and interpreted data.
- NE: assess spatial and temporal heterogeneity of deep vadose zone denitrification zones and effects on fate and transport of agricultural and industrial contaminants.
- MN: quantify the spatial distribution of chloride in groundwater and the contribution of groundwater seepage of chloride to surface waters.

1.8. Behaviors of emerging contaminants in soils

- MI, VA, NE: track the fate and transport of environmental contaminants in soil, water, and plant systems, including urban and irrigated cropping systems.
- CA: create new contaminant transport modules for the HYDRUS-1D model.
- CA: use reactive transport models that capture nitrogen cycling processes.
- CA: perform crop modeling to understand climate and hydrologic change impact on nitrogen and carbon cycling and nitrate leaching.
- WA, CT: analyze surface properties of micro- and nanoplastics in terrestrial systems; assess fate and transport of micro- and nanoplastics in soils
- OR: chemical and biological fingerprinting for contaminant source tracking

2. Apply soil physical and vadose zone concepts to improve soil and water management. (Applied science)

2.1. Applications to address soil function and soil resiliency (including climate change mitigation)

- CA: identify impact of regenerative agricultural practices on soil physical parameters and functioning.

- CA: assess impact of managed aquifer recharge on soil water and groundwater balance, soil health and water quality.
- NM: quantify response of SOC and N to different cover crops and mixtures in a limited irrigation winter wheat-sorghum-fallow rotation.
- FL: enhance our understanding of the water dynamics and hydraulic properties of sandy soils as well as their influence on agricultural water and nutrient management and sustainability of surface and groundwater resources.
- TX: enhance estimates of soil physical properties for soil health and groundwater management and prediction.
- NE: develop irrigation management and technologies to improve vadose zone water quality and aquifer protection.
- KY: improve nitrogen and irrigation management relative to landscape topography.

2.2. Address soil-related challenges within the water-food-energy-climate nexus

- TX, KS: use soil moisture information for improving agricultural production and decision making
- NM: measure effects of salinity on food and forage crops.
- TX: evaluate rootzone soil water dynamic under various agronomic practices/conditions in semiarid environments.
- CA: incorporate nitrogen in the water-energy-food nexus.
- CA: compare SWAT and HYDRUS modeling approaches to estimate nitrogen leaching from crop rotations with tomatoes under California conditions.
- VA: manage soil water content and infiltration in agricultural systems (e.g., vineyards, row crops).
- NM: optimize planting density and irrigation depth of hybrid maize seed production.
- NE: evaluate nitrates, salinity, and munition contamination in vadose zones underlying irrigated agricultural fields.
- AZ: have staged-release of gridded high-res (100m) hydraulic properties for the contiguous USA (700+ million points) based on Soil Grids with transition to NRCS-SOLUS-100/30.
- AZ: update and validate ensemble Pedotransfer functions with NRCS-NASIS data.
- AZ: quantify the potential for enhanced weathering in Arizona agricultural and rangeland systems.
- OR: integrate water harvesting from agrivoltaics with drywell-MAR to mitigate surface runoff, nutrient leaching, and alternative water for recharge.
- OR: use alternate water such as waste water for recharge and understand the change in soil properties and contaminant transport.

2.3. Physics of non-soils growing media for food production

- UT: improve plant growth media for "pick and eat" production in reduced gravity conditions.
- VA: quantify hydraulic properties of different soilless substrates to optimize irrigation strategies and rates.
- ID: recommend strategies for tension-based irrigation schemes.
- AZ: characterize/engineer optimal soilless substrates for soilless culture applications; simulate flow and transport processes in soilless substrates to optimize container geometry (i.e., prevent dead volumes) and irrigation management.
- FL: improve physical and hydraulic properties of sandy soils with domestic soil substrates.

2.4. Applying soil physics to assess or improve soil health

- LA, VA: explore effects of cover cropping management on soil water and nutrient stores and fluxes.
- FL: develop data-driven modeling tools for advancing soil health in agriculture, mitigation of climate change impacts, and the security and sustainability of soil and water resources.
- TX: evaluate impacts of soil health practices on soil physical properties, review on hydrologic impacts of soil health practices.
- NM: measure soil health changes due to land fallowing and addition of amendments.
- AZ: understand stockpiling of topsoil affects soil health in semiarid mining systems.

2.5. Soil moisture networks and their applications

- CA: measure water and nitrogen fluxes in agricultural fields; perform vadose zone monitoring (soil water tension, soil water content, soil water solution).
- WY: maintain a soil moisture and rainfall monitoring network in Wyoming rangelands and evaluate drought conditions.
- KS: maintain hydrological monitoring network at the Konza Prairie to study the connection between rootzone soil moisture and streamflow in tallgrass prairies; determine optimal *in situ* soil moisture monitoring depths.
- AZ: perform long-term modeling of soil moisture dynamics at NRCS SCAN sites using high-resolution soil hydraulic properties.
- OK: evaluate and improve soil moisture prediction algorithms for use in dynamic soil surveys.
- OK: develop applications of soil climate measurements and soil moisture predictions in forecasting streamflow and water table depth.

- OR: develop deep vadose zone sensor based monitoring for recharge estimation and contaminant transport.

2.6. Proximal and large-scale soil moisture sensing technologies

- KS, OK, TX: apply cosmic ray neutron sensors for proximal soil moisture estimation.
- AZ: estimate farm scale root zone soil moisture from remotely sensed reflectance.
- AZ: interpret SMAP data with high-resolution gridded hydraulic properties.
- FL: perform high-resolution profile soil moisture mapping with microwave proximal and remote sensors and AI techniques.

3. Develop new instrumentation, methodology, and models to characterize and interpret soil physical and vadose zone processes. (Methodology)

3.1. Sensor development

- DE: explore the potential of using VIS-NIR soil spectral measurement to develop a rapid tool for determining soil salinization for both saltine and non-saline soil.
- IA, NC: evaluate thermo-TDR sensors, impacts of salinity on measurements.
- UT: develop new electromagnetic sensing and measurement methods in soil.
- WI: develop *in situ* multi-functional soil moisture, nitrate, and temperature sensors.
- VA: perform field tests of low-cost systems to measure near-surface greenhouse gas emissions.

3.2. Sensor protocols and evaluation/inter-comparison

- KS, TX, OK: install *in situ* soil moisture sensor testbeds.
- TX: utilize acquired waveforms from the new Acclima TDR-315N sensor for the characterization of soil properties and to improve water content calibrations specific to a given soil.
- OR: develop a deep vadose zone monitoring network.
- UT, KS, TX: develop standards for electromagnetic-based sensor calibration and evaluation

3.3. Model-data fusion and integration for decision-support systems (including AI and robotics/IOT)

- CA: characterize hydrologic flow paths in mountainous areas using geochemical data and mixing models.

- KS: continue work on prototyping a deep neural network to quantify bare soil, green canopy cover, and crop residue using digital images.
- TX: perform field monitoring under different land use land covers for improved understanding of soil moisture, temperature, and carbon dynamics; develop new soil hydraulic response units using various satellite observations.
- AZ: develop short- and mid-term forecasts of actual evapotranspiration with deep learning.
- AZ: develop a novel physical-empirical model linking shortwave infrared reflectance and soil water retention.
- WI: integrate *in situ* soil moisture sensors and remote sensing data using machine learning and data assimilation for mapping soil moisture at high spatial (100-m) and temporal (daily) resolutions.
- CA: develop a modeling framework for plant response to different light spectra under agrivoltaics systems.
- TX: fuse data from satellite and in situ platforms to assess surface moisture spatiotemporal distributions, dry down patterns, and associated hydrologic fluxes (ET and baseflow) estimation.
- FL: integrate physical and data driven models for characterizing soil hydraulic properties and water flow.

3.4. Development and parameterization of process-based models that simulate soil and vadose zone processes

- VA: develop new theoretical and experimental framework to analyze gas diffusivity in soils and soilless substrates with non-uniform water contents.
- CA: continue HYDRUS model development.
- CA: improve vegetation parameterization in integrated groundwater-land surface models.
- KY: evaluate soil hydraulic property parameters within the Root Zone Water Quality Model (RZWQM2); assess spatial variability of soil physical properties and modeling of spatial soil hydrologic processes at different scales; parameterize and adapt multidimensional watershed model for decision support in water and nitrogen management.
- NE: identify the frequency and occurrence of funnel flows and denitrification hotspots in deep vadose zones.
- UT: develop new soil water flow equations using machine learning that go beyond Richardson-Richards Equation.
- WY: continue refinement of a numerical 1-D vertical coupled water-heat-solute flow and transport model for soils in cold regions.

3.5. Upscaling and downscaling of in situ, proximal, and remote sensing data for parameterization of models in the absence/scarcity of soil geodatabases.

- FL: integrate SMAP and SOLUS digital maps for real-time and high-resolution soil moisture mapping.
- KY: analyze crop yield, remotely sensed vegetation indices, topographic information and soil textural information at different resolutions to quantify the change of information of space-time relationships, and identify scales that effectively contribute to the improvement of management.

3.6. Apply geophysical tools to better quantify subsurface heterogeneity, hydrologically relevant properties, and groundwater and vadose zone interactions

- WY: evaluate different methods to predict subsurface hydraulic parameters using electrical resistivity tomography and seismic refraction data.
- NM: perform noninvasive geophysical and sensor methods for hyporheic zone characterization.
- NE, OR: characterize subsurface properties and heterogeneity using methods such as ERT, TEM, NMR, GPR, boreholes, and Nebraska GeoCloud.
- ID: integrate ERT and EMI measurements in irrigation design decisions.

3.7. Integration of sensor data, remote sensing data, in situ measurements across scales into scale-appropriate data analysis, modeling, and decision-support tools

- CA: compare land surface-based (mass balance) monitoring of water and nitrogen fluxes, (plot-scale, spatially repeated) vadose zone monitoring of water content, soil water tension, and nitrogen concentrations, and (large plot-scale, spatially repeated) shallow groundwater monitoring of water levels and nitrate concentrations.
- CA: compare modeling approaches for assessing spatially distributed (resolution: field scale/hydrologic response unit) basin-scale nitrate and salinity transport in recharge to groundwater: mass balance, HYDRUS, SWAT.
- KY: perform co-regionalization of soil measurements, soil and crop sensor data and remote sensing and their integration with landscape topography to parameterize 1-D (RZWQM2) and 3-D (SWAT) crop growth and soil process models for decision support.

4. Translate new concepts and methods to students, stakeholders, and the public. (Outreach, Extension, and Education)

4.1. Making our science more actionable for stakeholders and decision makers through knowledge translation, extension, and public outreach

- Perform field days (many locations)

- OR: develop and implement an action plan to reduce the nitrate concentration in groundwater less than 7 mg/L and repeal the GWMA status of the Lower Umatilla basin.
- CA: establish and implement a novel framework for the role of scientist communication in policy making.
- CA: perform an economic analysis of grower behavior under various groundwater salinization scenarios.
- CA: develop and implement groundwater sustainability plans for California groundwater basins.
- CA: develop and implement water quality guidance and decision-support tools for managers of agricultural or other managed aquifer recharge operations.
- ID: build out the Western Water Network.
- KY: Hold short courses for farmers, extension agents, and consultants to analyze field-scale data of yield maps, drone and satellite remote sensing and topographic elevation and convert them into management decisions.

4.2. Open-access and reproducible science (e.g., develop open data APIs, standardize data formats and protocols to integrate outputs across networks and test new datasets like Open ET)

- CA: develop a comprehensive framework and implement case study for measuring stream depletion of surface water due to groundwater pumping.
- AZ: continue annual releases of NRCS-SOLUS-based estimates of gridded soil hydraulic property Geotiff data, workflow annotations, and underlying Python/R code.
- CA: release source codes for web apps and web resources for diagnosis and improvement of saline and sodic soils.

4.3. Open-access educational resources

- OK: release open-source textbook “Rain or Shine”.
- CA: release web apps and web resources for diagnosis and improvement of saline and sodic soils

4.4. Improved pedagogy (teaching) methods (e.g., hands-on experiences like lab and field sessions)

- CA: hold HYDRUS short courses.

4.5. K-12 outreach and education

- TX: perform K-12 teacher trainings in St. Louis and Puerto Rico.
- VA: lead demonstration days on soil health with K-5 students in Virginia.

- WI: hold presentations at the Wisconsin Science Festivals and Ag Discovery Day to increase the public awareness of soil.

4.6. DEI and improving recruitment, retention of students in soil physics, hydrology, and environmental sciences

- TX: serve on ASA-CSSA-SSSA DEI committee, AGU Hydrology JEDI committee, SSSA K-12 committee.

Measurement of Progress and Results

Outputs

The research described herein will create outputs (which we define as activities, services, methods, approaches) that will significantly improve the science and applications of mass and energy transport in near-surface environments. These outputs include:

- New methods and approaches to study mass and energy transport processes in soils at spatial and temporal scales appropriate for effective resource management.
- New knowledge affecting the environmental impacts of soil, water and chemically-based agricultural practices and broader land uses.
- Methods to transfer results from non-destructive imaging into quantitative assessments of soil structure.
- New instruments and analytical techniques for measuring water, chemical, and energy fluxes.
- New tools and capabilities to quantify and monitor movement of agricultural contaminants from the vadose zone to ground water and to the atmosphere.
- New methodologies (computer and analytical models) that integrate knowledge of mass and energy transport, improving resource management.
- Plant growth media for reduced gravity environments of space.
- Sensitivity assessments of drip irrigation management scenarios to assist farmers and managers as they adopt sustainable and efficient irrigation systems.
- New thermal instruments and analytical methods for calculating sensible and latent heat fluxes including approaches to separate latent heat flux arising from evaporation and transpiration.
- New statistical methods to link crop yield and variability from sensor measurements.
- Updated versions of various numerical tools being developed: HYDRUS, HP1, CW2D module, the UNSATCHEM modules, the HYDRUS package for MODFLOW, SMART, and others.
- New collaborations with microbiologists, ecologists, hydrologists, pedologists, and engineers who are predicting landscape responses from land use/land cover changes and climate variability.

- Machine learning methods and tools to interpret large datasets from field studies and monitoring sites.
- Improved methods for uncertainty quantification
- Improved methods for data assimilation
- Further develop fiber optic DTS as a reliable soil moisture sensor.
- Continued support of young faculty, postdocs and students, who are dedicated to studying the role of soil physics in environmental processes.
- New graduate level, international course on soils in the global groundwater-agriculture interface.
- Strengthening of international collaborations, like the International Soil Modeling Consortium, that tie together many of the activities discussed herein.

Information on the scientific advancements, research findings, and inter-institutional collaborations throughout the world will be provided by an updated project website to be developed by a project member. This project will engage scientists and provide answers on short-term problems affecting US agriculture and environmental protection in the areas of salinity, water quality, solute transport, evapotranspiration, soil water and chemical transport properties and other areas, especially ecological processes. Our research will focus on long-term problems, such as identifying and characterizing the dominant processes affecting the transport of mass and energy through soils and other porous media at various management scales. This project is unique among multistate committee efforts because, rather than collaborating on a single focused objective, many collaborative projects are conducted simultaneously by organized groups of participating members and others. These extensive collaborations are established and maintained through our organizational structure. This strategy is inevitable given the diversity of problems addressed, but is also highly desirable, as information gained from the specific collaborations are shared with global science communities.

Projected Impacts

The breadth of research topical areas will lead to a diverse set of outcomes (which we define as results, impacts, and accomplishments) that will significantly improve our knowledge regarding mass and energy transport in near-surface environments. These outcomes will help us determine how to enhance soil sustainability and benefit society as follows:

- New scientific knowledge and information about fundamental physical, chemical and biological processes will help to understand the transformation and transport of pesticides, pathogens, colloids, nutrients, salts, and emerging contaminants.
- Results will quantify the amount, fate, and transport of bioactive compounds from commercial manure handling and disposal methods.
- Improved understanding of the role of scale in basin-scale processes, including evapotranspiration, water balance and ecological functions and services.
- Improved understanding of processes that control behavior of emerging contaminants from gray water or treated wastewater in soil/water systems, including mitigation practices.

- Examine herbicide leaching to groundwater versus metabolism in the soil and in plants in diverse climates.
- Evaluate impacts of plastics in soils and fate and transport of nano- and microplastics in soils.
- Guidance to producers on the sustainability of drip irrigation in salt-affected soils with reduced quantity or marginal quality irrigation water will be improved.
- Develop and demonstrate simple and reliable soil water sensing systems to accurately quantify soil water balance and other hydrological processes.
- Broader use of frequency-dependent dielectric measurements in soil to infer soil textural properties, in addition to water content and electrical conductivity.
- Improved measurement techniques will better characterize the relationships between soil, climate, and geomorphic position at the landscape scale.
- Improvements in the Evaluation and prediction of land-use changes on managed lands (impact of grazing on compaction, erodibility, plant communities).
- Landscape-scale predictive capabilities for soil evaporation implemented into large-scale climate models.
- Improved protection of soil and water resources from energy production (i.e., coal and mineral extraction, in particular mine tailings).
- Stronger connections developed between atmospheric measurements and soil physical and hydraulic properties, especially under climate change scenarios, will improve how soil processes are embedded into atmospheric models.
- Solution to the closure problem for various hydrologic fluxes, including heterogeneity adopted into lumped parameter models (i.e., SWAT).
- Establish statistical structure between soil water, soil carbon storage and soil gas (C, N) emission fluxes in different land use systems before and after land use transition.
- Assessments, briefings, and legislative testimony in direct support of policy and decision-making bodies at the state and federal level.

Milestones

2024

- First open data release of gridded soil hydraulic properties based on NRCS-SOLUS, including manuscript. Release of Maricopa Deep Infiltration data (open access)
- Determine surface properties and colloidal stabilities of different types of micro- and nanoplastics.
- Complete simulations of soil moisture dynamics at in situ monitoring stations nationwide using SOILWAT2 and TOPOFIRE.
- Complete development for methodology to downscale GRACE satellite total water storage anomaly to HUC-12 catchment scale.

- Publish the results from laboratory experiments aimed at quantifying gas diffusion rates and pore size distributions of nursery substrates.
- Complete development of the theoretical framework and initial results for quantifying hydraulic properties of porous media using tension infiltration.
- Quantification of changes in dynamic soil physical properties at various times throughout the growing season, and relationship to soil properties in undisturbed locations
- Development of remote-sensing based approach for detecting soil change based on land use type/change
- Quantify inter- and intra-sensor variability using in situ soil moisture sensor testbeds
- Complete K-12 teacher trainings on soil science topics in Puerto Rico at SSSA Summer Meeting

<u>2025</u>

- Second open data release of gridded soil hydraulic properties based on NRCS-SOLUS, including manuscript. Release of NRCS-NASIS-validated ensemble pedotransfer functions.
- Proof-of-concept decadal simulations of soil moisture dynamics as NRCS-SCAN locations.
- Quantification of transport characteristics of micro- and nanoplastics under both saturated and unsaturated flow conditions in porous media.
- Improve Oklahoma Automated Soil Information System (OASIS) and evaluate potential for nationwide expansion.
- Build and test a new system for monitoring soil particle movement during erosion.
- Test system for distributed measurements of CO2 fluxes using low-cost sensors.
- Application of field-scale soil moisture data for predicting soil cracking

<u>2026</u>

- Provisional third open data release of gridded soil hydraulic properties based on NRCS-SOLUS, including manuscript. Updated decadal simulations of soil moisture dynamics as NRCS-SCAN locations.
- Determination of colloidal stability of micro- and nanoplastics in soil and aqueous environments.
- Continue the development of modeling frameworks to understand soil water repellency and preferential flow processes in soils
- Complete development of preferential flow capable Green-Ampt type infiltration model.
- Complete watershed-scale cosmic-ray neutron rover surveys of soil moisture spatial distributions in four watersheds.
- Provide recommendations for vineyard soil management that enhances wine-grape quality.

<u>2027</u>

- Provisional simulations of decadal soil moisture dynamic at selected points within contiguous USA, consistent with SMAP.

- Determination of how the use of biodegradable plastic mulch films affect soil health.
- Use improved soil moisture datasets for streamflow forecasting and prediction of changes in groundwater levels.
- Complete development of peatland soil flow and transport model for simulation of methane and mercury export out of peatland soils.

<u>2028</u>

- Prepare and submit new proposal for 5-year project renewal.
- Complete mapping of concentration and residence time of chloride in groundwater of the Twin Cities Metro area.

Outreach Plan:

The project members comprise a group of dedicated soil, water and environmental scientists and engineers who excel in the communication of their research through different communications platforms, and who are active participants in soil and environmental research at universities and federal facilities across the country. For this multi-state project, we have developed a new objective (Objective 4) that specifically details many of the focal areas and activities that the project members will undertake as part of this project. Many of our members conduct workshops, short courses, and classes to educate other scientists and the public, and contribute to state, regional and federal agencies. They also lead undergraduate and graduate education and supervise research.Although most of our members do not have formal extension appointments, our members regularly participate in field days organized by extension faculty at the land grant universities. Our members are involved in publishing extension pamphlets, articles, and videos on their research projects. We are also involved in providing inputs to federal regulations pertinent to our research activities. For instance, our work on the environmental fate of microplastics helps the National Organic Standards Board to determine how to regulate the use of plastics in organic agriculture. Members of our group are actively involved in these discussions. As another instance, results of hydrologic and water quality modeling in agricultural production settings in southeastern Minnesota is being used to guide placement of nitrogen management BMPs intended to reduce nitrate transport to groundwater and surface water in the region.

W4188 members have published their findings in top-tier, peer-reviewed journals, targeting both science and engineering communities and are actively involved in organizing and participating many professional society international/national/regional meetings (SSSA, AGU, ESA, EGU, ASABE, ASCE, GRA, GSA), and major workshops and symposia sponsored by these societies. They serve as Editors and Associate Editors on journal editorial boards and as ad hoc manuscript reviewers, and therefore, enhance the overall quality of published research. Members also serve the scientific community by their engagement in competitive grant review panels of federal and regional entities, and as peer reviewers for domestic and international grant proposals. Our members have been instrumental in creating the International Soil Modeling Consortium, now with more than 600 members worldwide. They frequently engage with legislators at the state and federal level, and with managers, directors, and personnel in local, regional, state, and national water management organizations (e.g., irrigation and water districts, state agencies, regional MOUs) to support scientifically-based policy development and assist in technically sound decision-making. Through entrepreneurship, committee members have developed commercially available instruments, analytical tools, and textbooks. We fully expect this type of outreach to continue and thrive. Results of our work will be available through the annual project report, the project website (https://www.nimss.org/projects/18606), periodic joint meetings with related multistate research and/or coordinating groups, and through the international reputations and professional visibility of participants. The members will also work with consulting firms, companies and farmers to adopt measurement and management technologies.

Organization and Governance:

The current W4188 multistate committee consists of members representing universities, the USDA-ARS, National Laboratories, and other research units. In addition, visiting scientists (U.S. and global) participate along with member hosts. Officers of the new W5188 will be the Chair and Secretary. The Secretary is elected each year at the annual meeting and advances to Chair the following year. The Chair may appoint members to serve on subcommittees as needed.

Meetings will be approved by the Administrative Advisor. The current Secretary will be responsible for making local arrangements. Committee meetings typically have been held in Las Vegas, NV during early January, but members may decide (by voting) to choose new locations. Virtual and hybrid options have been offered since 2020. At each meeting, research accomplishments are reviewed, new opportunities and recommendations for multistate coordination/collaboration are discussed, and strategies for maximizing the impact of committee productivity are suggested. In addition, we invite scientists from different disciplines (e.g., geomorphology, land use planning, ecology) to provide opportunities for initiating transdisciplinary collaboration on new cutting-edge research directions that would engage areas of our expertise. In this way, fresh perspectives are injected into the committee, encouraging outward-looking and multi-disciplinary approaches toward pressing agricultural and environmental problems. The project committee and its precursors have had strong historical participation at the annual meetings (35-50 attendees, 59 in 2023), with new members inducted each year to ensure longevity and infusion of fresh perspectives. Although meeting attendance can vary from year to year, existing W4188 members have indicated a strong desire to continue participation.

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