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Special Section: UZIG Research: Land-Use and Climate Change Impacts on Vadose Zone Processes

UZIG Research: Measurement and Characterization of Unsaturated Zone Processes under Wide-Ranging Climates and Changing Conditions

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Unsaturated zone properties and processes are central to understanding the interacting effects of land-use change, contamination, and hydroclimate on our ability to grow food, sustain clean water supplies, and minimize loss of life and property. Advances in unsaturated zone science are being achieved through collaborations across traditional boundaries where information from biological, physical, and chemical disciplines is combined for new insights. The Unsaturated Zone Interest Group (UZIG) is an organization that exists principally to promote multidisciplinary collaborations and the sharing of ideas, expertise, and technical assets. Here we summarize key findings from 14 papers, several of which originated from a meeting convened by UZIG in 2017 at the University of Florida in Gainesville titled "Land-Use Change, Climate Change, and Hydrologic Extremes: Unsaturated Zone Responses and Feedbacks." This special section of *Vadose Zone Journal* contains multidisciplinary research in three general categories relevant to measuring and understanding unsaturated zone responses to changing land uses and climate: (i) unsaturated zone properties and processes; (ii) soil–plant–atmosphere interactions; and (iii) novel field sampling devices. A strong cross-cutting theme in these papers is the value of continuous monitoring data and ways of utilizing them to discover novel hydrologic, biologic, and pedologic information. As climatic and land-use conditions change and demands for resources and stresses on ecosystems continue to intensify, it is vital to improve our fundamental understanding of the processes at work in the unsaturated zone. Toward that goal, we discuss the need for improved ground-based unsaturated zone monitoring networks.

Abbreviations: UZIG, Unsaturated Zone Interest Group.

Core Ideas

- This special section reviews Unsaturated Zone Interest Group (UZIG) multidisciplinary research.
- These studies summarize UZIG studies on vadose zone properties and processes.
- They summarize soil–plant–atmosphere processes and present two novel field sampling devices.
- The need emerges for a consistent ground-based unsaturated zone monitoring network.

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This special section contains papers describing recent advances in field, modeling, and data assimilation approaches for observing and understanding unsaturated zone processes. These papers examine fundamental unsaturated zone processes and improved methods of characterization that can address questions concerning land use and climate change, emphasizing processes and tools more than comparative land use or climatic trend analysis. The papers fall into three general themes: (i) unsaturated zone properties and processes; (ii) soil–plant–atmosphere interactions; and (iii) novel field sampling devices. Some papers clearly fit into one of these themes, others fit well into more than one theme. The special section contains 14 papers, several of which originated from a 2017 meeting convened by the Unsaturated Zone Interest Group (UZIG) at the University of Florida in Gainesville titled "Land-Use Change, Climate Change, and Hydrologic Extremes: Unsaturated Zone Responses and Feedbacks."

The contributions to this special section are diverse, demonstrate the multidisciplinary nature of unsaturated zone research, and reflect the efforts of UZIG to promote collaborations. Unsaturated zone scientists commonly have academic backgrounds in hydrology, agriculture, soil mechanics, fluid mechanics, engineering, or various other fields, often with additional expertise in biology, physics, chemistry, geology, or mathematics (Nimmo et al., 2009). The practical applications of unsaturated zone research are diverse and include contaminated site remediation and management, agricultural production and regulation, water supply quantity and quality, natural resource management, natural hazards mitigation, and many more. Tools and methods available for investigating the unsaturated zone are ever-changing and include laboratory and field experiments, environmental monitoring, data analysis, theoretical development, and numerical simulation. Recent advancements in in situ and remote sensing technologies have greatly improved our ability to observe the unsaturated zone at scales ranging from individual pores a few microns in aperture to watersheds and regions spanning hundreds of kilometers.

The UZIG was initiated in 1987 as a topical interest group within the USGS. At that time, some of those involved had unsaturated zone expertise but often specialized toward soil science applications, while others had hydrologic expertise but were unfamiliar with the complexities of water and contaminant transport under unsaturated conditions (Nimmo et al., 2009). Since its inception, UZIG has expanded, with participants from universities and other institutions, in keeping with its goal of bridging institutional and international boundaries. The UZIG promotes multidisciplinary collaborations and sharing of ideas, expertise, and technical assets. Its mission is to advance unsaturated zone science by fostering information exchange and collaborative studies across multiple research groups and organizations. This is accomplished through scientific presentations, discussion sessions, hands-on meetings, field trips, and publications such as this special section, coordinated by UZIG and partner institutions.

In This Special Section

Unsaturated Zone Properties and Processes

The papers in this category focus on the physical properties of water flow through the unsaturated zone. The processes discussed have implications for several aspects of human and ecological health under a changing climate including: water quality, landslide hazards, water availability, and water use efficiency.

Two papers examine preferential flow through soils. Smith and Capel (2018) present a field study from Iowa in which they used specific conductance, soil volumetric water content, and discharge data from a subsurface agricultural tile drain to differentiate soil preferential flow paths from matrix flow paths in silt loam and silty clay loam soils underlying row crops. They present a specific conductance end-member mixing analysis, which demonstrates that a significant portion of discharge from the subsurface drain can be attributed to preferential flow, mainly through macropores or other largely open pathways. Their results demonstrate that macropore flow begins shortly after the initiation of rainfall, well before smaller pores are saturated and surface ponding occurs.

Orozco-López et al. (2018) review concepts, limitations, and perspectives on riparian unsaturated zone preferential flow. Riparian ecosystems are hotspots for macropore flow, which can reduce the effectiveness of riparian buffers for mitigating pollution. Experimental and modeling techniques are still lacking to characterize the morphologies of in situ riparian unsaturated zone macropore networks at the soil profile and landscape scales. They stress the need for well-controlled field experiments using the latest monitoring technology to quantify and better understand preferential flow in the riparian zone. They conclude that with new data and resulting developments, decision-support tools can better predict the influence of preferential flow on the performance of riparian buffers in improving surface water quality.

A series of four papers illustrate the value of high-temporal-resolution, in situ time series monitoring data for improved quantification of unsaturated zone properties and water flow through the unsaturated zone. Ebel et al. (2018) compare laboratory and field-based estimates of soil-water retention properties under wetting and drying conditions for soils in the Oregon Coast Range. Differences in soil hydraulic behavior between wetting and drying conditions (i.e., hydraulic hysteresis) may be important in landslide triggering. They found that hydraulic hysteresis was overestimated under laboratory conditions compared with field data. They then compared the results of a hydrologic process model parameterized first with the laboratory-based data and then with the field-based data. They found that unsaturated hydraulic parameter estimates from in situ field data may lead to more accurate simulation of the hydrologic response to rainfall. They also recommend that some experimental manipulation in the field to promote very dry and very wet conditions may be necessary to achieve the broader range of hydrologic conditions needed for estimating hysteretic unsaturated hydraulic properties.

Bean et al. (2018) examine pattern recognition and machine learning techniques for extracting field capacity values from continuous soil moisture time series data. Field capacity is an important soil hydraulic property, with many practical implications in the context of plant water stress and irrigated agriculture. The estimation of field capacity requires identification of complete soil-water cycles in the data, which has primarily been accomplished with time-consuming expert review of the data. In this study, the authors compare automated methods that (i) identify complete soil-water cycles and (ii) estimate field capacity. The entire process can be completed with free, open-source software. They identify temporal variations in field capacity and demonstrate the need for automated, objective analysis to improve irrigation management.

Gowdish and Muñoz-Carpena (2018) developed and tested a modified Green–Ampt infiltration model for simulating transient point-source infiltration and redistribution in a quasi-three-dimensional (3D) flow domain. This model provides information for understanding heterogenous soil water infiltration and redistribution patterns from point sources, which is important in many settings like crop drip fertigation, wastewater disposal, and mitigation of climate-induced coastal salinization. The model, 3D Modified Green–Ampt with Redistribution (3DMGAR), compared well with HYDRUS-2D numerical solutions of the Richards equation for a broad range of soils. The 3DMGAR's ability to accurately simulate infiltration and redistribution from point-source water applications is important for improving water-application efficiency and decreasing chemical leaching from these applications, especially where solutions to the Richards equation become highly nonlinear, such as in well-drained soils.

Nimmo and Perkins (2018) present an approach for automated analysis of surface-water and groundwater hydrographs that can quantify hydrologically important fluxes. Watershed-response metrics such as stormflow, baseflow, and aquifer recharge can be extracted from continuous data by examining the rate of change during water-table or streamflow recession. The approach uses a parameterized framework for decision-making during hydrograph evaluations to maximize objectivity and consistency and to reduce the ambiguity of subjective judgement. Episodic recession and input fluxes are estimated automatically by extrapolating master recession curves and integrating hydrograph components in coupled surface water and groundwater systems. This structured, iterative approach not only expedites simultaneous analysis of watershed-scale drainage properties using both surface water and groundwater input data but also provides a framework for documenting the necessary subjective judgements involved in hydrograph analysis.

In two complementary papers, Dickinson and Ferré (2018a, 2018b) present modeling approaches to estimate the travel time of periodic infiltration events through the unsaturated zone and the conditions under which water flux (groundwater recharge) becomes steady. These papers provide insight into how potential changes in precipitation patterns might affect infiltration through the unsaturated zone and, ultimately, groundwater recharge. Their first paper presents an algebraic method for quantifying how water fluxes through a layered unsaturated zone varies with the magnitude and timing of precipitation. This approach builds on a previous method by Bakker and Nieber (2009) for homogenous soils. Dickinson and Ferré (2018a, 2018b) provide a concise overview of their algebraic method and compare it with model results from HYDRUS-1D for several layered-soil scenarios. Their second paper (2018b) presents a freely available screening tool to visualize and conceptualize how precipitation pulse signals are damped through a layered unsaturated zone, eventually reaching a steady recharge rate. They apply their methods to the Central Valley of California and identify areas where precipitation pulses are damped in the unsaturated zone and groundwater recharge rates are approximately steady.

Conaway et al. (2018) explore fundamental processes of soil vapor transport and production in the unsaturated zone. They evaluate the spatial distribution of CO_2, CH_4, and the isotopic composition of CO_2 ($\delta^{13}C$-CO_2) in shallow and deep sampling sites within and adjacent to a low-level radioactive waste disposal site. Multiple sources of CO_2 and CH_4 were identified across sampling locations and provide insight into observed gas distributions and vapor transport mechanisms. Three CO_2 sources were distinguished from isotopic compositions of CO_2–C in soil vapor: the root zone, deep soil gas, and microbial respiration of waste buried at the site. The distribution of CH_4 reflects atmospheric sources, production in anaerobic microzones in the waste disposal area, and methanotrophy in the undisturbed shallow subsurface outside the waste disposal area. Differences in CO_2 and CH_4 distributions were explained by the sources identified and interactions of the gases with pore water. The results imply that CH_4 and $\delta^{13}C$-CO_2 may serve as good tracers of anthropogenic effects in the unsaturated zone even when CO_2 primarily reflects natural processes.

Soil–Plant–Atmosphere Interactions

Three papers examine interactions across the soil–plant–atmosphere interface. Two of these use extensive field data to demonstrate possible improvements in irrigation practices. Agricultural producers in Florida face the challenge of providing crops with adequate water to ensure productivity while minimizing the risk of crop damage from shallow water tables following rain. The third paper addresses hydrologic, ecologic, and pedologic impacts of stream-channel disturbance through land-use change.

Da Silva et al. (2018) present methods for determining optimum water table depths at which upward water flux from the saturated zone meets crop evapotranspiration demand at different stages of crop development. The methods utilize extensive field data from four areas irrigated with different systems in Florida. The episodic master recharge method (Nimmo et al., 2015) is used for evaluating the water table response to rain events to inform water table level control decisions before and after rain events. They provide insights for minimizing wasteful water use when irrigating crops grown in areas with shallow water tables and variable precipitation.

Cardenas and Dukes (2018) evaluate the performance of rain sensors in regulating irrigation application between rainfall events in Florida using field experiments and modeling. Rain sensors interrupt scheduled irrigation after rainfall of a certain magnitude and then allow irrigation to proceed after a dry-out period. Modeled soil dry-out times were nearly three to five times longer than the rain sensor dry-out times, suggesting that the sensors allowed irrigation to resume too soon following a rain event. They recommend the development of an electronic mechanism to delay the resumption of irrigation, which could reduce irrigation by 22 to 27%.

Perkins et al. (2018) demonstrate with field experiments how emplacement of transportation infrastructure has modified the ecohydrologic system in the Mojave Desert. Ephemeral stream channels that have been cut off from upslope water sources were shown to be associated with reduced perennial plant cover and have altered infiltration properties. Microbial and vegetation assemblages have changed with these hydrologic alterations, and microbial populations in the abandoned channels may signal an initial form of soil development. Deeper rooting plants are more abundant where streams continue to flow ephemerally and they can access increased soil-water storage.

Novel Field Sampling Devices

Two papers present novel field sampling devices that enable better measurements of the unsaturated zone. Smith and Kean (2018) present a design and successful application of an apparatus for automated in situ tensiometer refilling. Under suction, a tensiometer's internal liquid is drawn from its porous cup; under positive pressure, pore water infiltrates into the cup and dissolved gases are released. Over time, either of these phenomena cause unreliable readings, which require costly site visits for continued data collection. Their system uses a water reservoir and solenoid valves to remotely refill tensiometers and avoid costly site visits. The device was installed and tested at a post-wildfire hydrologic monitoring site in the Angeles National Forest in southern California.

Trost et al. (2018) present the design of a direct-push freezing core barrel for collecting samples of coarse-textured sediments with adjacent pore water. The device uses liquid CO_2 to freeze the bottom 10 cm of a 122-cm core sample. The frozen plug retains sediments and fluids within a polyvinyl chloride core sleeve and minimizes fluid redistribution. The device can be used interchangeably with unsaturated-zone direct-push tool strings. This enables core collection for studies of contaminant transport and transformation in both unsaturated and saturated profiles where detailed characterization of fluid chemistry, geochemistry, and microbial communities in narrow reaction zones is needed.

An Emergent Theme

An important theme that emerged during the meeting and through the papers in this special section is the value of and need for continuous, consistent, and long-term monitoring data in the unsaturated zone. More than half of the papers in this special section utilized high-resolution, field data sets for observing in situ processes and are examples of the types of discoveries that are possible with investments in data. The papers meet the challenge of generating novel and useful hydrologic information from increasingly abundant but often bewildering and unwieldy data resources. Automated (or near-automated) methods used for processing high-resolution datasets produced hydrologic information ranging from plot-scale field capacity estimates (Bean et al., 2018) to watershed-scale hydrologic fluxes (Nimmo and Perkins, 2018). Most of the investigators used open-source coding software such as R (R Core Team, 2016) to conduct their analyses, thus making the techniques of analysis readily adaptable and widely available to scientists, regulators, and resource managers. These kinds of advances in measurement approaches, data acquisition capabilities, and automated analysis techniques are critical to ongoing and future advances in the Earth sciences, particularly in the context of a changing climate and the increasing frequency and magnitude of extreme hydroclimatic events.

However, the sparse coverage of publicly available soil moisture data and the difficulty in assimilating diverse data sets of varying quality impedes scientific discovery in hydrology. In a review, Vereecken et al. (2010) argued for better access to field monitoring soil moisture data, improved methods that fully exploit the information in soil moisture data, and the development of upscaling methods that combine hydrogeophysical measurements with remote sensing. Presently, for example, federal agencies in the United States provide nationally consistent data from far fewer unsaturated zone observation sites (e.g., soil moisture) compared with other major portions of the water cycle including surface water, groundwater, and precipitation (National Integrated Drought Information System, 2018; USGS 2018a, 2018b). The USDA and NOAA, currently the primary agencies for collecting in situ soil moisture data, collectively provide web-accessible, quality-assured soil moisture data for fewer than 400 unsaturated zone observation sites compared with thousands of real-time surface-water and groundwater observation sites from the USGS (National Integrated Drought Information System, 2018; USGS 2018a, 2018b). While there is a strong need for additional measurements, especially in systematic and methodologically consistent networks, there is a concurrent need for the data to be made publicly available from existing observation sites. There are thousands of soil moisture monitoring sites in the United States (in addition to the federal agency sites listed above), some of which are part of local or regional networks with publicly available data but many of which are private datasets used for agricultural production, horticultural activities, lawn maintenance, or other land management activities.

Investments in unsaturated zone data, such as an improved ground-based soil moisture monitoring network, will propel scientific discoveries at scales relevant for understanding unsaturated zone responses to changing land use and climate. For example, data assimilation methods can be developed that incorporate fundamental unsaturated zone processes to spatially extensive remote sensing data. Although advances in methods such as microwave remote sensing of soil moisture (e.g., NASA's SMAP and the European Space Agency's SMOS missions) can provide broad spatial scale and time-varying estimates of soil moisture (Mohanty et al., 2013, 2017), significant limitations exist for downscaling these to scales relevant for local management issues. Major shortcomings include coarse space and time resolution, shallow penetration depth, and mismatched governing hydrologic principles (Mohanty et al., 2017). Scientists can work toward resolving these shortcomings with hydrologic information derived from comprehensive ground-based soil moisture monitoring data.

The bridging of institutional boundaries through efforts like those of UZIG is essential to bring together the many different agencies, scientists, and private citizens that manage disparate stations and networks to produce a valuable information resource of consistent soil moisture data. The new International Soil Moisture Network is a step in the right direction for consolidating a vast array of soil moisture monitoring data sets, but in the United States, the coverage of the available datasets is still sparse (International Soil Moisture Network, 2018).

Concluding Remarks

The papers included in this special section represent a cross-section of the research done by UZIG scientists and demonstrate the UZIG's goal of bridging institutional and traditional discipline boundaries. The papers explore a range of topics that fall into three general categories: unsaturated zone properties and processes, soil–plant–atmosphere interactions, and novel field sampling devices. A strong cross-cutting theme is the value of high-resolution data and ways of utilizing it to discover novel hydrologic, biologic, and pedologic information that aids our understanding of processes such as contaminant transport, watershed-scale water movement, and triggering of landslides.

As climatic and land-use conditions change, and demands for resources and stresses on ecosystems continue to intensify, it is vital to improve our fundamental knowledge of the processes at work in the unsaturated zone. An improved ground-based soil moisture monitoring network, for example, would provide such critical information. The UZIG supports the need for advancing unsaturated zone science by providing informative opportunities for scientists to connect and develop collaborations.

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