Preview of Award 1331726 - Annual Project Report

Cover

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Submitting Official (if other than PD\PI):	**Susan L Brantley** **Principal Investigator**
Submission Date:	**10/01/2018**
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	**Susan L Brantley**

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Accomplishments

* What are the major goals of the project?

Overall Project: We are learning to earthcast the CZ. To us, earthcasting means developing quantitative models for earth surface evolution that will enable us to project into the future. We plan to do this by creating models to describe fluxes we see today, by testing the models by hindcasting the geologic record, and then using those models to make forecasts. We focus on a 165 km2 watershed in central PA (Shavers Creek). We have developed an observational model to measure important aspects of the CZ in this large watershed. Over short timescales and large spatial extents, we are developing an atmosphere-land surface model that couples meteorological and ecological processes with hydrological and biogeochemical processes in regolith using information about i) depth to bedrock; ii) permeability; iii) water uptake by roots; iv) distribution of fractures and macropores. Over long timescales and smaller spatial extents, we are developing models that predict these regolith characteristics. The models that treat these various processes are built on the Penn State Integrated Hydrologic Model (PIHM). With different modules in PIHM we plan to model changes in water, energy, sediment, and solute (WESS) fluxes at various timescales. For the sedimentary rocks underlying our CZO, we use these models to explore how the geological past has impacted the structure of regolith, and, in turn, how this structure contributes toward controlling today's fluxes.

While working on this big picture effort, we have structured our group into 9 teams, identified by 9 driving hypotheses, as described below.

H1 Team Goal: The H1 team is testing the following hypothesis while measuring fracture distributions, using measurements of cosmogenics to assess erosion rates; using boreholes, field observations, and geophysics to predict the structure of porosity and permeability in Shavers Creek watershed and surrounding relevant sites: H1. ***Feedbacks among frost shattering, weathering reactions, and the evolution of topography have resulted in an asymmetric distribution of fractures that in turn controls the observed differences in fluid flow in the subsurface between the sun-facing and shaded sides of catchments within Shale Hills and much of the Susquehanna River Basin.*** *(Kirby, Bierman, DiBiase, West, Brantley, Lin)*

H2 Team Goal: This team is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the distribution of soil gases, soil moisture, and organic acids and their effects on weathering of regolith in the Shavers Creek watershed: H2. ***The distribution of weathering reactions across a landscape can be described as a function of biotic and abiotic production and consumption of acids (CO_2, DOC) and O_2.*** *(Kaye, Brantley, Eissenstat, Li)*

H3 Team Goal: Team H3 is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the distribution of tree roots and their effects on water cycling, weathering, fungal distribution, macropores, erosion, and tree throw in the Shavers Creek watershed: H3. ***Trees with deeper roots (oaks) are associated with less frequent tree throw, slower hillslope erosion rates, fewer vertical macropores, faster weathering at depth, and deeper regolith than trees with shallower roots (maples).*** *(Eissenstat, Davis, Kaye, Brantley)*

H4 Team Goal: This team is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the distribution of regolith and macropores in regolith and their controls on fluid flow among the lithologies within the Shavers Creek watershed. H4. ***Macropores are important in controlling fluid flow and chemistry in soils derived from various lithologies, but the nature and effects of these macropores differ significantly among shale, calcareous shale, and sandstone.*** *(Lin, Duffy, Eissenstat, Davis)*

H5 Team Goal: Team H5 is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the controls on regolith chemistry and mineralogy using a reactive transport model developed for simulation of regolith formation: H5. ***Greater evapotranspiration on the sunny, north side of Shale Hills means that less water recharges to the stream, explaining why Mg and other cations are less depleted in the regolith on the north compared to the south hillslopes.*** *(Li, Brantley, Kaye, Russo)*

H6 Team Goal: Team H6 is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the controls on solute concentrations in stream waters of subcatchments within the Shavers Creek watershed, using a reactive transport modelling approach: H6. ***Ions that are released quickly from ion exchange sites (Mg, Na, K) throughout the catchment demonstrate chemostatic behavior (~constant concentration in the stream), whereas Fe, Mn, and DOC concentrations vary with changes in watershed-stream connectivity.*** *(Russo, Brantley, Li, Kaye, Shi, Duffy) Tess Russo is leaving Penn State.*

H7 Team Goal: This team is testing the following hypothesis while developing as complete a dataset as possible that allows understanding of the fluxes of carbon and water in the Shavers Creek watershed using PIHM modelling: H7. ***Land-atmosphere fluxes of carbon (C) and water, ground-water hydrology, and ecosystem change are coupled processes at time scales of months to decades. This coupling varies with the lithology and land use and position on the hillslope****. (Davis, Shi, Eissenstat, Duffy, Lin, Kaye)*

H8 Team Goal: The H8 team is testing the following hypothesis while developing as complete a dataset as possible that allows multi-scale modelling to project physical processes from Shale Hills to Shavers Creek: H8. ***Co-located, intensive, relocatable measurements of soil moisture, tree sap flux, sapwood area, LAI, ground water depth, temperature, ^{18}O and D/H along with a 4-component radiometer, laser precipitation monitor and landscape-level soil moisture (COSMOS) can be assimilated within a multi-scale distributed modeling framework to project physical processes from Shale Hills to Shavers Creek to Young Woman's Creek and Snake Creek watersheds.*** *(Shi, Duffy, Davis, Eissenstat, Lin, Duffy)* Chris Duffy has indicated he would like to have minimal involvement with the CZO other than with respect to PIHM modelling. Instead, Yuning Shi, who has been involved in the CZO since its inception and now works part time on the project, is leading the H8 team in collaboration with Li Li.

H9 Team Goal: The H9 team is spearheading measurements to understand weathering processes in the target catchments and using models to earthcast weathering and other CZ processes into the future while testing the following: H9. ***Increasing atmospheric CO_2 in the future will cause higher temperatures and faster weathering of clays in the catchment, increasing streamwater solute loads.*** *(Brantley, Godderis, Li, Duffy, Davis, Shi)* Pam Sullivan was a postdoctoral student working on this project and she is now an assistant professor at University of Kansas where she is writing up two papers on CZO research. Two seed grants provided data for this team effort. A USGS Seed Grant funded Carleton Bern and the Kent State Seed Grant was used by E. Herndon at Kent State to evaluate the spatial distribution of dissolved and colloidal elements in soils, groundwater, and surface water in the SSHCZO catchment.

* What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

Major Activities:

Overall Major Activities

The entire team has made large advances in measuring and modelling our target landscape within the CZO. We have also made our first steps toward upscaling. In addition, the entire team helped run the Arlington meeting -- National Critical Zone Science Workshop: Current Advances & Future Opportunities -- and we helped publish the paper in Earth Surface Dynamics describing a proposed design for a CZO network. Finally, we also published our paper from our tree workshop. Also during this year, we completed publication of the fourth paper that was written by one of our seed grantees. Specifically, we gave seed grants to outside scientists to work at our CZO and each group of scientists have now published papers from their work at the CZO. We gave each of those groups funding from our NSF funds.

Our major activities for this past year are described below for each team.

H1. The H1 team has begun working at the agricultural subcatchment (Cole Farm), with the goal of distinguishing anthropogenic versus periglacial drivers of hillslope erosion and colluvial valley aggradation. MS Student Perri Silverhart (advised by R. DiBiase) has collected soil samples for 137Cs analysis along two opposing hillslope transects at Cole Farm to quantify decadal patterns of erosion and deposition, with measurement beginning in fall 2018. Topographic analysis using lidar data, analysis of historical air photos, and field mapping of soil thickness provide additional constraints on land use history and critical zone architecture. We continued collaborations with J. Hayes (Dickinson College) and G. Mount (Indiana University of Pennsylvania) to collect shallow seismic and electrical resistivity tomography data at Cole Farm in summer 2018. At the sandstone catchment (Garner Run), we continued synthesizing geophysical data collected in 2016/2017, and are nearing submission of a manuscript in collaboration with J. Hayes (Dickinson College), X. Comas (Florida Atlantic University), and G. Mount (Indiana University of Pennsylvania). At Bear Meadows, a sandstone site near Garner Run, we conducted exploratory geophysical and drilling work to characterize spatial patterns in periglacial colluvium thickness in a site that is better situated for the long-term preservation of sediments recording landscape response to Pleistocene climate forcing. At Young Womans Creek, a 220 km^2 watershed north of Shavers Creek draining the Appalachian Plateau, we completed geologic mapping, stratigraphic analysis, and topographic analysis to complement detrital cosmogenic ^{10}Be analysis done by former MS student A. Denn (U. of Vermont). From this work a paper led by R. DiBiase was submitted in summer 2018 to Earth and Planetary Science Letters and is currently in revision (DiBiase et al., in revision).

H2. The H2 team: 1) published one paper on the N cycle in Shale Hills (Weitzman and Kaye 2018), 2) sampled pore fluid over the year in one shale and one sandstone catchment for a comparison study, 3) established GroundHOG sampling locations at a new agricultural watershed (Cole Farm), 4) sample soil pore fluid at all three catchments (shale forest, sandstone forest, calcareous shale agricultural) for the 2018 growing season, 5) designed and implemented a new study of the effect of windthrown trees on the depth distribution of soil C and forest regeneration, 6) trained two graduate students (Caitlin Hodges, PhD; Ben Dillner, MS), 7) collected new soil cores for extraction of Fe and Mn to test hypotheses regarding links between metals and C across two CZOs (Shale Hills and Calhoun).

H3. The H3 team: 1) Finished analysis of the vertical root distribution of trees as affected by shale and sandstone including tree species identification of root distribution by DNA extraction 2) published a paper arising from the Tree Workshop (3) contributed to the broader project goals of tracking leaf phenology, litter fall, green leaf chemistry, radial tree growth, sap flux and soil moisture in the Shale Hills and Garner Run catchments. This team also contributed to understanding root length density and soil respiration as influenced by topography on shale and how mycorrhizal type (Arbuscular mycorrhizal (AM) or ectomycorrhizal (EM)), hillslope position and lithology affect wood decomposition. (4) In addition, this group tested whether roots decompose faster with roots present or not on different lithologies and how much site of origin of the woody debris influences its decomposition (i.e., “home field advantage”).

H4. The H4 team: 1) published 3 papers related to the Shale Hills catchment in collaboration with other team members (see publication list), 2) set up two new soil moisture monitoring sites at the Shale Hills and the Garner Run to test the microtopography controls on macropore flow.

H5. The H5 team 1) developed a code (RT-FLUX-PIHM) that simulates hydrological and geochemical processes at the watershed scale, 2) used RT-Flux-PIHM to understand the concentration discharge relationships for Cl and Mg at Shale Hills, 3) is developing a reactive transport model for a hillslope catena to understand soil development in Shale Hills.

H6. The H6 team 1) continued stream discharge and chemistry, groundwater and soil water chemistry data collection at Cole Farm and along the main branch of Shavers Creek; 2) integrated stream, spring, and groundwater measurements to develop a conceptual model of the controls on shallow subsurface and deeper groundwater fluid and solute transport at Cole Farm; 3) conducted synoptic steam solute and discharge measurement sampling campaigns along the full length of Shaver’s Creek within the CZO; 4) assessed the capability of geospatial and statistical methods to predict stream solute chemistry using readily available spatial datasets.

H7. The H7 team 1) continued to maintain the eddy covariance flux data streams from the Shale Hills watershed (forested, shale bedrock) and Cole Farm (agricultural watershed, calcareous shale bedrock), 2) ran and evaluated the coupled Flux-PIHM-BGC watershed energy-hydrology-biogeochemistry modeling system for Shale Hills watershed, and 3) continued to work towards a multivariate carbon-water data assimilation system that can be applied to the coupled Flux-PIHM-BGC modeling system, and can describe, with good accuracy and precision, the coupled carbon-water-nitrogen cycle in complex topography.

H8. The H8 team 1) conducted hydrological connectivity and discharge-storage relationship analyses using the calibrated land surface and hydrologic model - Flux-PIHM (Penn State Integrated Hydrologic Model with a land surface module) - at Shale Hills and Garner Run; 2) Assessed the relative strength of topography and lithology using the swap experiments based on properties at two sites (results presented at the 2017 AGU Fall meeting and a manuscript has been submitted to WRR); 3) Tested differences between using the COSMOS and the frequency domain reflectometry (FDR) soil moisture measurements in constraining the hydrologic model (Flux-PIHM) with both the Hornberger–Spear–Young (HSY) algorithm and a data assimilation system (the ensemble Kalman filter); 4) Evaluated the influence of measurement locations in constraining the model used the same methods mentioned in 4); 5) Utilized the fast Fourier transform (FFT) to perform the time-frequency analysis on soil moisture time series, which leads to tease out the time representativeness of each soil moisture measurement; 6) Installed a new COSMOS probe in a Cole Farm; 7) performed Flux-PIHM simulations for the Cole Farm; 8) performed Flux-PIHM with deep groundwater simulation for Shale Hills.

H9. The H9 team 1) finished and published two papers on the importance of particle transport in Shale Hills (one of these was published by seed grantee Carleton Bern; 2) submitted a paper describing how we can earthcast weathering and how to use reactive transport modelling in describing weathering at Shale Hills.

Specific Objectives:

Specific Objectives Overall

During the last year, our overall specific objective was to begin the collection of data at the agricultural site and to begin to pull together the data from all teams into upscaling models using the PIHM code.

Specific Objectives Enumerated by Team

H1. Initial fieldwork at the Cole Farm (agricultural) catchment is underway, and soil samples from more than 10 pits have been collected and prepared for 137Cs measurement at Penn State.

H2. The main specific objectives were to 1) repeatedly sample pore chemistry and gas along the three GroundHOG catenas, 2) test mechanisms that explain variation in soil pore chemistry, and 3) publish research on the N cycle and nitrous oxide fluxes at Shale Hills, 3) sample pits and mounds of windthrown trees in shale hills.

H3. Tree and shrub species were determined for the roots collected from soil pits in Shale Hills and Garner Run catchments as well as in sandstone and shale sites in the Tuscarora State Forest in south central Pennsylvania. With respect to coarse woody debris, the goal was to determine whether roots, tree mycorrhizal type, or soil lithology play an essential role in wood decomposition. Also, does coarse wood debris decompose faster under its native canopy, versus an away canopy. We also investigated the role and production of root exudates based on local conditions. We dug two pits, one in the Shale Hills Catchment, and one in the Garner Run Catchment and have gathered samples that will need analysis to determine organic acid content e.g. phosphatase. We have also examined broader vegetation impacts by sampling 25 forest plots (315 meters square) tree basal area, age and radial growth (based on increment cores) with equal distributed across Rose Hill shale and Tuscarora sandstone to assess forest growth on different lithologies in response to annual variation in temperature and precipitation.

H4. The specific objectives of H4 included the goals i) to comprehensively understand the major space-time factors that govern the occurrence and dynamics of macropore/preferential flow; ii) to develop new field methods of detecting and quantifying preferential flow occurrence; and iii) to enhance the comparison of preferential flow patterns across monitoring sites and catchments.

H5. The specific objective of this team was to develop a quantitative model of regolith formation and to relate observations in the CZO to this model.

H6. The first primary objective was to expand monitoring within the newest subcatchment, Cole Farm, to include deep groundwater, while continuing to measure spring and river water chemistry. The second primary objective was to determine whether litholoIgy and land use datasets are predictors of stream water chemistry within the greater Shaver's Creek watershed.

H7. The team finished testing the response of the carbon stocks and fluxes to environmental forcing (soil temperature, soil moisture, light, soil hydraulic properties, nutrient availability) using the Biome-BGC ecosystem biogeochemistry model, and in the coupled Flux-PIHM-BGC modeling system, within the Shale Hills watershed.

H8. The team continued to evaluate hydrologic model parameter transferability from Shale Hills to Garner Run; to understand differences in hydrologic processes with different lithology and topography; and to test "must-measure" parameters for hydrologic models using model-data synthesis.

H9. The team has been finishing the writing and publication of the papers on earthcasting and subsurface particle transport.

Significant Results:

Significant Results Overall

Overall, our team is starting to understand how to model coupled land surface observations and hydrology using our new suite of PIHM codes. We have been working with Rutgers scientist Ying Fan to understand how to incorporate our new knowledge into earth systems models. With the new publication of carbon, water, nitrogen, and manganese budgets for Shale Hills, and the development of our full modelling capabilities, we are poised to provide real leadership for incorporating the relevant aspects of the CZ into earth systems models. This year, we also discovered that root density is approximately 2-fold higher on shale than sandstone while aboveground vegetation biomass on the two lithologies are similar -- this is a surprising result that points to how little we understand about the near surface, and how geological characteristics may be very important in determining what we observe above ground.

Significant Results Enumerated by Team

H1. Our analysis of Young Womans Creek (DiBiase et al., in revision) has resulted in three significant results that are of broad interest to understanding how stratigraphy influences landscape response to base level fall. First, our dense nested sampling strategy for detrital cosmogenic ^{10}Be and lidar-based geologic mapping enabled us to robustly constrain the best-fit spatial pattern of erosion rates at Young Womans Creek using a novel ^{10}Be flux modeling approach. Second, this pattern of erosion rates highlights how the presence of a resistant sandstone caprock sustains steep topography in underlying weak rocks, enabled by the armoring of hillslopes and channels by large clasts. Third, the resulting pattern of topography, stratigraphy, and erosion rates at Young Womans Creek shows how layered rocks lead to complex landscape response to base level fall, with implications for interpreting topography at the SSHCZO and more broadly.

H2. From our measurements of N cycling, we discovered that: Topographically convergent flow path locations had significantly higher surface N2O flux rates than nonconvergent flow path locations in the summer, but this was not true in other seasons. Overall, N2O fluxes were a large percentage (~19%) of total ecosystem N losses, and nearly twice as large as stream N export. Following decades of anthropogenic atmospheric deposition and additional N from shale weathering, watershed N inputs (~8 kgN ha-1 yr-1) are greater than outputs (~3.7 kgN ha-1 yr-1). We published two papers that summarize the nitrogen budget for Shale Hills.

H3. Root density was approximately 2-fold higher on shale than sandstone while aboveground vegetation biomass on the two lithologies were similar. Oaks tend to have deeper roots than maples on sandstone but not on shale. These findings contributed to a paper that has been accepted by the Vadose Zone Journal (Li Li et al. 2018). It will also contribute to a paper that is currently in progress that focuses on the importance of lithology on root distribution in co-occurring tree species (Szink et al. in prep). The overall advantages of a particular mycorrhizal type (AM or EM) and root type (e.g., thin vs. thick) shifts depending on nutrient heterogeneity in the forest ecosystem (Chen et al. 2018). Regardless of tree mycorrhizal type, roots enhance decomposition of coarse woody debris and decomposition is faster on shale than limestone.

H4. The H4 team summarized the dominant controls of macropore/preferential flow across various soils and landscapes and developed a framework of six key categories of controls to assess the susceptibility of various soils to preferential flow. We proposed a new method to offset the influence of the number of sensors per site on the detected occurrence frequency of preferential flow using real-time soil moisture data (this enhances the comparison study of preferential flow pattern across CZOs). We also proposed a new 3-D fill-and-spill conceptual model for the Shale Hills catchment. We compared the difference in preferential flow in Ground HOG transects between Shale Hills and Garner Run catchments. We tested the potential of integrating thermal imaging, repeated GPR scanning, and real-time monitoring to detect the occurrence of preferential flow at Shale Hills and Garner Run.

H5. The team has developed a new code, RT-Flux-PIHM, the first of its kind to simulate hydrogeochemistry with detailed multi-component reactive transport processes at the watershed scale. Two papers have been published about this advance in WRR: one on model development, the other on using the model to understand CQ dynamics.

H6. Expansion of monitoring sites along tributaries and the main step of Shaver's Creek to quantify relationships between solute chemistry and catchment area lithology and land use. Masters student Callum Wayman will complete his thesis on this topic in Fall 2018.

H7. Both the coupled Flux-PIHM-BGC modeling system and the stand-alone BiomeBGC modeling have shown that, according to these modeling systems, the interactions between the nitrogen and water cycles is the dominant environmental control on spatial structure in carbon stocks in the Shale Hills watershed. Tree growth appears to be limited both by water and nitrogen availability, especially at the ridge tops. The stand-alone model underestimates the ridge-top to valley floor gradients in carbon, especiallyunderestimateding gradients in the soil carbon pool. The Flux-PIHM-BGC model is able to represent the spatial variations in terrestrial carbon processes, and the predictions of watershed average soil carbon and vegetation carbon compares well with observations.

For both modeling systems, the watershed average biomass pools (above and below ground carbon) and net ecosystem productivity are optimized in our model by using the observed carbon residence time (aboveground biomass divided by above ground net primary productivity), the observed nitrogen deposition rate, and tuning the soil carbon pool decomposition rate.

Research to determine the set of observations needed to simulate the spatial variability in carbon cycle stocks and fluxes with precision and accuracy is in progress, as is research to evaluate the robustness of the existing modeling systems with respect to a broader range of watershed observations, including spatial and temporal changes in soil respiration.

H8. Lithology controls the non-linearity of the discharge-storage relationship and threshold behavior of connectivity. The GR -- with sandy soils -- and a large riparian zone has a larger dynamic water storage and is less responsive to transient rainfall patterns. Direct model parameter transfer between catchments cannot reproduce monthly discharge until incorporating measured boulder distribution. The data from COSMOS shows a less flashy response due to its large footprint showing a better representativeness at the catchment scale; it also measures a higher soil moisture during the winter because of its representation of both liquid and frozen water. The measured FDR SM at the hillslope and the COSMOS SM are consistent with the Flux-PIHM simulated total water storage dynamics at the whole watershed, whereas the valley floor FDR shows more transient dynamics between influx from the upland and out fluxes (Q and ET). The dynamics of SM at the valley floor must be measured. The COSMOS records the large water content in the vegetation during the summer, which masks the response of soil moisture to transient precipitation events.

H9. The H9 team produced two papers describing the very important result that when shales weather, particles move in the subsurface. To date, no models of weathering and erosion include subsurface particle transport...however, we have shown that this type of transport is very important, especially for shales. This is a very significant finding because it could affect the interpretation of cosmogenic isotopes and our understanding of erosion.

Key outcomes or Other achievements:

Overall Key Outcomes or Other Achievements

The entire team helped run the Arlington meeting -- National Critical Zone Science Workshop: Current Advances & Future Opportunities -- and we helped publish the paper in Earth Surface Dynamics describing a proposed design for a CZO network (Brantley, S.L., McDowell, W.H., W.E., D., White, T.S., Kumar, P., Anderson, S.P., Chorover, J., Lohse, K.A., Bales, R.C., Richter, D.D., Grant, G. and Gaillardet, J., 2017. Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth. Earth Surface Dynamics, 5: 841-860, doi:10.5194/esurf-5-841-2017). Finally, we also published our paper from our tree workshop (Brantley, S.L., Eissenstat;, D.M., Marshall;, J.A., Godsey;, S.E., Balogh-Brunstad;, Z., Karwan;, D.L., Papuga;, S.A., Roering;, J., Dawson;, T.E., Evaristo;, J., Chadwick;, O., McDonnell;, J.J. and Weathers, K.C., 2017. Reviews and syntheses: on the roles trees play in building and plumbing the critical zone. Biogeosciences, 14: 5115-5142, doi.org/10.5194/bg-14-5115-2017). This year also marked the year that the majority of our seed grantees published papers on their seed projects using dollars given by NSF to Penn State. Specifically, we gave seed grants to outside scientists to work at our CZO and the majority of the group of scientists have now published papers from their work at the CZO.

The Principal Investigator was awarded the Urey Prize, the highest prize of the European Association of Geochemistry, for her lifetime of work, and she was cited for her work on critical zone science in particular.

Key Outcomes or Other Achievements Enumerated by Team

H1. The key outcomes of the H1 team include: 1) 2 papers published on periglacial controls on erosion rates (Denn et al., 2018; Del Vecchio et al., in press) and 1 paper submitted on rock strength controls on erosion rate and topography at Young Womans Creek (DiBiase et al., in revision); 2) Collaborations started in summer 2016 have continued with multiple shallow geophysics field campaigns consisting of teams of PSU graduate students and postdocs, undergraduate students from IUP and Dickinson, and faculty from all three institutions. Results from Garner Run have been synthesized in a manuscript that is in final preparation for submission in early fall 2018.

H2. We contributed soil pore chemistry data from Shale Hills and Garner Run to a team publication that used pore water cation concentrations to enhance understanding of concentration-discharge relationships (Hoagland et al. 2017). We published a paper on the N cycle at Shale Hills (Weitzman and Kaye 2018). Our graduate student (Caitlin Hodges) received a SAVI award for cross-CZO research. Our research revealed patterns of N cycling that are distinct from many other watersheds that have been extensively studied to understand N saturation; despite showing no other symptoms of N saturation, the watershed had high upland N2O losses, especially in convergent flow paths during summer. High upland N gas losses may be a mechanism that maintains N limitation to biota in the Shale Hills catchment. From our measurements of CO2/O2 we discovered that: At shale hills, most soils have a CO2/O2 concentration ratio that reflects aerobic respiration. However, in wet growing seasons and every spring, CO2/O2 deviates from the signal expected from aerobic respiration alone, suggesting other processes produce and consume soil CO2 and O2. At Garner Run, the CO2/O2 ratios for most of the year reflect some level of anaerobic respiration, which is surprising because O2 concentrations remain > 18% most of the time. At Garner Run, the signal of anaerobic respiration even when O2 concentrations are high could result from microsite heterogeneity in soils. That is, while soil macropores may reflect high bulk O2 concentrations, micropores may be anaerobic leading to a shift in the CO2/O2 ratio.

H4. The team published 2 papers related to soil moisture in the Shale Hills catchment (Guo and Lin, 2018, Guo et al., 2018) and contributed to three other published articles.

H5. The team has a paper published on regolith development on black shale (Heidari et al., 2017, GCA) as part of the SSHCZO's shale transect, and two papers on CQ relationships in Shale Hills published in WRR. In addition, the student on this project, Dacheng Xiao, presented his hillslope modeling work at AGU 2017, and won the AGU Fall meeting Outstanding Student Paper Award.

H7. The team developed a new coupled modeling system, Flux-PIHM-BGC, available for research. It includes a coupled simulation of groundwater hydrology, biogeochemistry, and surface energy balance. A paper on Flux-PIHM-BGC development and testing was published in *Ecological Modelling*. This new coupled model is being used to explore our observations about the importance of nitrogen in controlling carbon stocks in the watershed. The eddy covariance flux data record from Shale Hills is continually updated as observations are collected. The Cole Farm flux record is now being processed. Two papers on simulating carbon in complex terrain and model parameters sensitivity analysis are in preparation.

H8. The H8 team developed a version of Flux-PIHM with deep groundwater representation and implemented the model at Shale Hills. The team also produced Flux-PIHM input for Cole Farm that can be used for land surface and hydrologic studies.

H9. Pam Sullivan is now an Assistant Professor at Univ of Kansas and she is working with us to use the reactive transport code WITCH to earthcast the future of weathering in the context of climate change. We are working to publish a paper on this ...it is in late stage review...where we discuss how aspect can be used as a way to test the effect of climate on weathering. We also outline how to earthcast weathering.

* What opportunities for training and professional development has the project provided?

The CZO is used by several classes at Penn State and is visited by faculty and students from several local universities (e.g., Kent State Univ., Lehigh Univ., Univ of Pennsylvania, Indiana Univ of Pennsylvania, Dickinson College, Temple Univ., Rutgers Univ.) for research and teaching.

The CZO was also home base for the NSF funded GEOPATHS field experience (2-week multi-institutional near-surface geophysics applied field experience) focused on addressing ongoing geophysical questions in critical zone science. Seventeen students from Rutgers/Temple and 4 peer mentors participated in this initial year and the project is funded for two additional years. Faculty collaborations between outside team members have grown from this project, contributing to the ideas outlined and developed in the two articles accepted to the Vadose Zone Journal Special Edition: Hydrological Observatories. The effort is focussed on students from under-represented groups to expose them to geophysical research and field research.

<u>Training and Professional Development within Each Team is Listed Below</u>

H1. Graduate student P. Silverhart started her MS and graduate student J. Del Vecchio started her PhD, both at Penn State with R. DiBiase. Graduate student P. Silverhart was mentored in geomorphic mapping using fieldwork, GIS and lidar analysis, and in the interpretation and preparation of soil samples for 137Cs analysis. In spring 2018, J. Del Vecchio mentored one undergraduate researcher through the NASA Pennsylvania Space Grant Women in Science and Engineering Research (WISER) program.

H2. In fall 2017 the H2 team recruited two new graduate students to the hypothesis. Caitlin Hodges is a PhD student in soil science and as noted above, she received a SAVI grant in 2018 for cross CZO research. Ben Dillner is an MS student and he is conducting research on pits and mounds of windthrown trees. Both are in the department of Ecosystem Science and Management.

H3. The H3 team provided opportunity for undergraduate (Molly Pash) to work on a study entitled "Effects of topography on soil moisture and belowground carbon processes". Rondy Malik went on a sponsored post-doctoral visit at The University of Kansas, courtesy of Joy K. Ward and James D. Bever at the Department of Ecology and Evolutionary Biology.

H4. Five visiting scholars were trained to use GPR, EMI, TDR, and infiltrometers at the Shale Hills and Garner Run catchments.

H5. The team graduated a PhD student, Chen Bao, who is now working in industry. Another student, Dacheng Xiao, is working on the hillslope model. Both students have benefitted from monthly SSHCZO seminar and cross-disciplinary discussions. A previous student mentored by this team, Peyman Heidari, is now a professor at Missouri Univ. of Science and Technology.

H6. A graduate student, Beth Hoagland, co-advised by Russo and Brantley, had her first lead author manuscript published in *Water Resources Research* covering work on C-Q at the sandstone catchment. A second graduate student, also advised by Brantley and co-mentored by Russo (Callum Wayman), has collaborated across Colleges within Penn State to refine his research on modeling solute transport, and has presented results at a national conference. A third graduate student (Virginia Marcon) also worked on one of the subcatchments of the CZO to understand weathering and water-rock interaction.

H7. Doctoral student Yuting He participated in CZO meetings and workshops, and international and national-scale research conferences, and made significant progress toward completing her dissertation. One paper is nearly ready to submit, a second is in draft form, and a third body of research work is well underway. Her doctoral committee includes three members of the CZO team (Davis, Eissenstat, Shi), a global climate scientist, and a watershed hydrologist.

H8. A graduate student Dacheng Xiao (co-advised by L. Li and Y. Shi) was trained to systematically analyze the watershed hydrological dynamics and synthesize field observations for hydrologic modeling. Xiao also was trained in scientific writing. Graduate student Callum Wayman was trained to use PIHMgis to prepare input files for PIHM. Undergraduate Mike Forgeng (in Geosciences) is writing a senior thesis while working at Cole Farm and the mainstem of Shavers Creek. Undergraduate Nathan Carpenter completed a senior thesis in Geosciences on soils in Cole Farm.

H9. Graduate student (and now postdoc) Xin Gu helped collect data and write the paper that was published in Earth and Planetary Science Letters on subsurface particle transport. Postdoc Hyojin Kim wrote that paper. She now works in Denmark in a permanent position. Pam Sullivan, now an Assistant Professor at Univ of KS, is writing the earthcasting paper. She has had the opportunity to work with Yves Godderis. Godderis is the writer of the WITCH code and he works for CNRS in Toulouse France. Her work using WITCH was facilitated over the years by several trips to France to work with Yves, including trips funded by the CZO.

* How have the results been disseminated to communities of interest?

The entire CZO team helped run the Arlington meeting -- National Critical Zone Science Workshop: Current Advances & Future Opportunities -- and we helped publish the paper in Earth Surface Dynamics describing a proposed design for a CZO network. Finally, we also published our paper from our tree workshop. Also during this year, we completed publication of the fourth paper that was written by one of our seed grantees. Specifically, we gave seed grants to outside scientists to work at our CZO and each group of scientists have now published papers from their work at the CZO. We gave each of those groups funding from our NSF funds.

The team, and especially Program Coordinator Jennifer Williams, continued to work with the TeenShale Network, which involves high school students learning about shale gas. Presentations were given to students at the State College Area High School. Three high school teachers are actively involved and the effort is now providing a credit for a class at the high school. The effort resulted in a publication:

Williams, J.Z., Dykhoff, S., Pollak, J., Brantley, S.L. (2017) ONLINE E XTRA: Bringing the Outdoors In: Application of Hydrogeology Education Tools, *In the Trenches*, Volume 7,number 4, Exploring the Critical Zone, Earth's Outer Skin, (https://nagt.org/nagt/publications/trenches/v7-n4/online_extra.html)

The CZO team is working with the Shavers Creek Discovery Center to set up their new museum using many principles from critical zone science.

The Principal Investigator was invited to discuss CZOs as an approach for investigating the environment at the 1) 2017 Gordon Conference on Catchment Science: Interactions of Hydrology, Biology & Geochemistry, 2) at the National Critical Zone Science Workshop: Current Advances & Future Opportunities in Arlington, 3) at a panel entitled, Using the Critical Zone Observatory Network to Put Geology into Environmental Science, at the American Geophysical Union, 4) as a CZO representative at the DOE Collaborative Design Challenge workshop in Bethesda, Md, April 2017.

The Principal Investigator also received the Urey Prize, the highest price of the European Assoc of Geochemistry and gave an invited talk, Exploring subsurface geochemical landscapes in the critical zone, at the 2017 Goldschmidt conference. This talk included discussion of a new paradigm (associating subsurface water flow with reaction fronts, and highlighted work at 5 CZOs.

Dissemination activities from the hypothesis teams are summarized below.

H1. Key results of the geomorphic mapping and cosmogenic dating at Garner Run were presented at AGU in fall 2017 by J. Del Vecchio. J. Del Vecchio continued work with the Shavers Creek Environmental Center to integrate CZO research with public science exhibits. In October 2017, The 82nd Field Conference of Pennsylvania Geologists was held in State College, PA, and focued heavily on work done as part of the CZO. Over 200 participants spanning academia, government, and industry visited the CZO field site.

H2. The H2 team leader (J. Kaye) has been participating in the Soil Microbiology cross CZO Working group to disseminate and learn CZO approaches. Team members gave several talks on campus and at other venues. Two publications on this hypothesis disseminated results to the scientific community. In addition, we contributed to two team publications in the Vadose Zone Journal that disseminated general results to the scientific community. We contributed to two tours of Shale Hills, including the PA Geologists field tour and a tour for an undergraduate “Forest Soils” class. We hosted Kathleen Lohse from the Reynolds Creek CZO, including a tour of all three of our research catchments.

H3. Work on vertical root distribution was disseminated at the AGU Annual Fall Meeting (2017) and the effects of roots on wood decomposition at the Annual Meeting of the American Society of Botany (Botany 2018). Work at the Shale Hills CZO was also disseminated at a DOE PI meeting associated with a DOE grant at the site. Work presented included how topography can strongly affect aboveground biomass partitioning without strongly affecting root length partitioning. We also presented on the coupling of Biome BGC with PHIM. Work on root and mycorrhizal fungal biology was disseminated at meetings for the general public and Extension agents (e.g. Private Land Owners). Work on tree growth was presented to REU students associated with Prof. Erica Smithwick’s project in the summer.

H4. H4 produced 2 publications (European Journal of Soil Science, Advances in Agronomy), contributed to 1 publications (Vadose Zone Journal), and 3 presentations (AGU Fall Meeting (Qicheng Tang, Ismaiel Szink and Li Guo)

H5. The team has been actively advocating the use of models to understand complex systems and general principles across CZOs. Specifically, i) The team, together with Russo and Hoagland (H6 team), is actively involved in a Cross-CZO C-Q relationship workshop; ii) Li has developed an online reactive transport modeling (RTM) course that has been and will be used to teach graduate students across CZOs. The online course has been taught three times in Spring 2016, 2017, and 2018. With further refinement, Li plans to make all course materials public in 2019 so that anyone who is interested in using RTM can access it without the limit of time and space. To the best of the team’s knowledge, this is the first RTM online course, which has the potential for teaching the next generation of scientist RTM tools for CZO work; iii) Li also led a forward- looking manuscript “Expanding the role of reactive transport models in Critical Zone Processes”, which was published in 2017. This manuscript comes out of an RTM workshop (together with Kate Maher and Alexis Navarre-Sitchler) in 2014. iv) Li organized an AGU session “Modeling the Critical Zone: Integrating processes and data across disciplines and across scales” together with Harry Vereecken (Bonn University, Germany), Praveen Kumar (UIUC, IML CZO), and Arora Bhavna (LBNL, East River Watershed) in December 2017.

H6. A paper was published in *Water Resources Research* in the C-Q special issue comparing the apparent controls on C-Q behavior by the hyporheic zone and hillslopes in the sandstone and shale catchments, respectively. Graduate student, Callum Wayman, presented his research on modeling solute transport across watershed scales at the American Geophysical Union fall meeting, 2017, and has submitted an abstract to present his final results at the same conference in fall 2018.

H7. The team has presented research results at the CZO All-Hands meeting and as contributions to the team colloquium series. Doctoral student He presented a talk in the CZO_LTER_NEON_ISMC cross network workshop. Doctoral student He presented a poster at the 5th iLEAPS science conference held in Oxford, UK and Gordon Research Conference on catchment science. Two manuscripts will be submitted shortly. Shi presented a talk at 2017 AGU fall meeting on Flux-PIHM-BGC development and evaluation at Shale Hills. A manuscript on Flux-PIHM-BGC development and test at Shale Hills was published in *Ecological Modelling*.

H8. Team members gave talks on campus and at other venues (e.g. 2017 AGU Fall Meeting). A manuscript titled “Contrasting water storage and connectivity in first-order catchments of differing lithology and topography” have been submitted to Water Resources Research.

H9. Two papers have been published on particle transport at Shale Hills and one paper is under review about earthcasting.

* What do you plan to do during the next reporting period to accomplish the goals?

Overall, the team is packaging up the work on upscaling and modelling the CZ into papers for the community. We are also refining our ideas as to how to upscale models from small Shale Hills-scale to large Shavers Creek-scale.

H1. Roman DiBiase is leading a group paper on shallow geophysical surveying in Garner Run, which is in final preparation for submission in early fall 2018. Soil samples collected from Cole Farm will be analyzed for 137Cs in fall/winter 2018/2019 by graduate student P. Silverhart. Also at Cole Farm, a soil coring campaign in the 2-4 m thick valley fill is planned for fall 2018, with 137Cs and radiocarbon analysis of deposits planned for winter 2018/2019. These data will help constrain the timing of valley aggradation at Cole Farm and help assess whether this aggradation is due to periglacial climate forcing or recent anthropogenic influence. At Bear Meadows, a preliminary core collected in summer 2018 will be analyzed for cosmogenic ^{10}Be and ^{26}Al by J. Del Vecchio, P. Bierman, and R. DiBiase, as part of a seed project funded by the Penn State Institute of Energy and the Environment.

H2. We have now accumulated a significant dataset from several landscape positions and three lithologies that show variation in CO2/O2 ratios, and those data must be analyzed. We have used data from two of the catchments (sandstone and shale forests) to develop a hypothesis about the role of Fe and Mn in the C cycle, and our graduate student (Caitlin Hodges) received SAVI funding to support the testing of this hypothesis. She has already collected samples from Shale Hills and Calhoun and in the coming year she will complete analyses. We expect to publish one paper on CO2/O2 ratios and a collaborative paper on the P cycle at Garner Run. These results point to two testable hypotheses: 1) At shale hills, microbial reduction of Fe and Mn may cause shifts in the CO2/O2 signal in the late growing season and those metals may stay reduced over winter. Then in spring, as soils dry, Fe and Mn may be oxidized again (abiotically) to repeat the cycle. 2) At Garner Run, the signal of anaerobic respiration even when O2 concentrations are high could result from microsite heterogeneity in soils. That is, while soil macropores may reflect high bulk O2 concentrations, micropores may be anaerobic leading to a shift in the CO2/O2 ratio.

H3. The team will publish work on tree species composition of roots in relation to soil depth along the catenas in sandstone and shale and submit at least two papers associated with the influence of topography on root respiration and root length density. They will help the broader research efforts by continuing to monitor soil moisture, sap flux, litter fall, LAI and tree diameter growth. The team will also contribute one paper in collaboration with other hypothesis groups on the soil-plant-atmosphere continuum in regards to soil moisture, sap flux and eddy covariance measures of evapotranspiration. They will also initiate studies to examine the influence of lithology, tree species and soil depth on root exudation and factors controlling wood decomposition. The tree team is starting to work with the model-development team to create a root-water module for the PIHM suite of models. Provide estimates of aboveground carbon storage on a mass per unit area on sandstone and shale that will permit modeling the sensitivity of forest growth investigating to annual variation in temperature and precipitation. Microbial metagenomic analysis will be used to unravel factors that help govern home-field advantages (HFA) of coarse wood debris decomposition. This includes characterizing microbial communities in woody plant tissue, as well as home and away soil communities.

H4. The team will also test the microtopography control on preferential flow by utilizing the new soil moisture sensors. We will continue to test the use of COSMOS as a way to measure soil moisture, and in this endeavor we are working with the US Army who is interested in this technique. (Predicting soil moisture is important for the Army in terms of predicting where mud forms in undeveloped areas).

H5. The team will continue model development of regolith formation. 1D ridgetop simulations will be run to model regolith formation at Shale Hills, and if time permits, for the sandstone and calcareous shale lithologies. Hillslope catena models will be developed for simulation of shale, and if time permits, for the sandstone and calcareous shale lithologies.

H6. The team will support monitoring of GroundHOG instruments at the agricultural site, which will provide necessary pore water and soil moisture data for modeling fluid and solute transport within the catchment. The current graduate student working on H6 will develop conceptual and quantitative hydrologic models for the agricultural site, and begin using field data and remote sensing products to develop a scaled up model characterizing C-Q behavior in the greater Shaver's Creek watershed. Callum Wayman will publish a manuscript on his work quantifying stream solute chemistry as a function of lithology and land use. The team will also assist the cross-CZO postdoctoral researcher conducting hydrologic studies across the network. Virginia Marcon will publish a paper on the water-rock interaction in the Garner Run subcatchment: she will emphasize the importance of dust input into watersheds and how shale and quartzite are impacted differently by such dust inputs.

H7. Research work will be expanded to include further model-data comparison (nitrogen cycle, soil respiration, carbon stock uncertainty assessment) and, if warranted, additional field data collection to refine our understanding of the carbon-water-nutrient interactions within the Shale Hills watershed. We will use spatially distributed soil respiration measurements to evaluate further BiomeBGCs parameterizations of the soil carbon cycle across the watershed. We will attempt to evaluate the nitrogen cycle processes suggested by our coupled modeling system with field nitrogen cycle observations. We will complete a model sensitivity study that will prioritize observations needed to simulate the watershed carbon and nitrogen cycles at Shale Hills. This work moves us towards the objective of a data assimilation system for coupled watershed hydrology and biogeochemistry. We are expecting to perform cross-catchment tests of this modeling system within the SSHCZO, and cross-CZO Flux-PIHM-BGC tests to evaluate the robustness of this modeling system.

H8. Based on the understanding of water, energy, sediment, and solute fluxes at Shale Hills and Garner Run, the strategy of simulating Shaver's Creek with less intensive measurements will be evaluated. The Flux-PIHM model with deep groundwater will be tested at Cole Farm.

H9. The team plans to publish the earthcasting paper (Pam Sullivan, first author).

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Products

Books

Book Chapters

Billings SL, Sullivan PL (2018). Working across scales to project soil biogeochemical responses to climate. *Multi-scale Biogeochemical Processes in Soil Ecosystems: Critical Reactions and Resilience to Climate Changes* . Status = UNDER_REVIEW; Acknowledgement of Federal Support = Yes ; Peer Reviewed = Yes

Guo, L., & Lin, H. (2018). Addressing Two Bottlenecks to Advance the Understanding of Preferential Flow in Soils. In Advances in Agronomy. *Advances in Agronomy* 147. Academic Press Inc.. 61. Status = PUBLISHED; Acknowledgement of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/bs.agron.2017.10.002.

Sullivan PL, Li L, Goddéris Y, Brantley SL. 2018. (2018). Poised to Hindcast and Earthcast the Effect of Climate on the Critical Zone: Shale Hills as a Model. *Biogeochemical Cycles: Ecological Drivers and Environmental Impact.* . Status = UNDER_REVIEW; Acknowledgement of Federal Support = Yes ; Peer Reviewed = Yes

Inventions

Journals or Juried Conference Papers

Bao, C., Li, L., Shi, Y., Duffy, C. (2017). Understanding watershed hydrogeochemistry: 1. Development of RT-Flux-PIHM. *Water Resources Research*. 53 (3), 2328. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/2016WR018934

Bern, Carleton R. and Yesavage, Tiffany (2018). Dual-phase mass balance modeling of small mineral particle losses from sedimentary rock-derived soils. *Chemical Geology*. 476 441–455. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.chemgeo.2017.11.040

Brantley Susan, White Timothy, West Nicole, Williams Jennifer, Forsythe Brandon, Shapich Dan, Kaye Jason, Lin Hangsheng (Henry), Shi Yuning, Kaye Margot, Herndon Elizabeth, Davis Kenneth, He Yuting, Eissenstat David, Weitzman Julie, DiBiase Roman, Li Li, Reed Warren, Brubaker Kristen, Gu Xin (2018). Susquehanna Shale Hills Critical Zone Observatory: Shale Hills in the Context of Shaver's Creek Watershed. *Vadose Zone Journal - Special Section - Hydrologic Observatories*. . Status = ACCEPTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Brantley, S.L., McDowell, W.H., Dietrich, W.E., White, T.S., Kumar, P., Anderson, S., Chorover, J., Lohse, K.A., Bales, R.C., Richter, D., Grant, G., and Gaillardet, J. (2017). Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth. *Earth Surface Dynamics*. 5 841. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.5194/esurf-5-841-2017

Brubaker, Kristen M., Johnson, Quincey K. and Kaye, Margot W. (2018). Spatial patterns of tree and shrub biomass in a deciduous forest using leaf-off and leaf-on lidar. *Canadian Journal of Forest Research*. 48 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1139/cjfr-2018-0033

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Del Vecchio, J., DiBiase, R.A., Denn, A.R., and Bierman, P.R. (2018). A record of coupled hillslope and channel response to Pleistocene periglacial erosion in a sandstone headwater valley, central Pennsylvania. *Geological Society of America Bulletin*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1130/B31912.1

Denn, Alison R., Bierman, Paul R., Kirby, Eric, Zimmerman, Susan R. H., and Caffee, Marc W. (2017). Cosmogenic 10Be indicates that periglacial boulder fields are ancient, multigenerational features. *GSA Today*. 28 4. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1130/GSATG340A.1

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Guo, L., Fan, B., Zhang, J., & Lin, H. (2018). Occurrence of subsurface lateral flow in the Shale Hills Catchment indicated by a soil water mass balance method.. *European Journal of Soil Science*. 69 (5), 771. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1111/ejss.12701

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Jin, L., Ma, L., Dere, A., White, T., Mathur, R., and Brantley, S. (2017). REE mobility and fractionation during shale weathering along a climate gradient. *Chemical Geology*. 466 352. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.chemgeo.2017.06.024

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Li Li, DiBiase Roman A., Del Vecchio Joanmarie, Marcon Virginia, Hoagland Beth, Xiao Dacheng, Wayman Callum, Tang Qicheng, He Yuting, Silverhart Perri, Szink Ismaiel, Forsythe Brandon, Williams Jennifer Z., Shapich Dan, Mount Gregory J., Kaye Jason, Guo Li, Lin Henry, Eissenstat David, Dere Ashlee, Brubaker Kristen, Kaye Margot, Davis Kenneth J., Brantley Susan L. (2018). Investigating the Effect of Lithology and Agriculture at the Susquehanna Shale Hills Critical Zone Observatory (SSHCZO): The Garner Run and Cole Farm Subcatchments. *Vadose Zone Journal - Special Section - Hydrologic Observatories*. . Status = ACCEPTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

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Sullivan, P., Godderis, Y., Shi, Y., Gu, X., Schott, J., Hasenmueller, E.A., Kaye, J., Duffy, C., Jin, L., and Brantley, S.L. (2018). Exploring the effect of aspect to inform future earthcasts of climate-driven changes in weathering of shale. *Journal of Geophysical Research - Earth Surface*. . Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

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Williams Jennifer Z., Dykhoff Sharon, Pollak Jonathan, and Brantley Susan L. (2017). Bringing the Outdoors In: Application of Hydrogeology Education Tools. In The Trenches, 7(4):online. *NAGT - In The Trenches*. 7 (4), . Status = PUBLISHED; Acknowledgment of Federal Support = No ; Peer Reviewed = No ; OTHER: https://nagt.org/nagt/publications/trenches/v7-n4/online_extra.html

Wymore, Adam S., Nicole R. West, Kate Maher, Pamela L. Sullivan, Adrian Harpold, Diana Karwan, Jill A. Marshall, Julia Perdrial, Daniella M. Rempe and Lin Ma (2017). Growing new generations of critical zone scientists. *Earth Surface Processes and Landforms*. 42 (14), 2498. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/esp.4196

Xiao, D., Shi, Y., Brantley, S., Li, L. (2018). Contrasting water storage and connectivity in first-order catchments of differing lithology and topography.. *Submitted to WRR.*. . Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Zarif, F., Kessouri, P., and Slater, L. (2017). Recommendations for field-scale induced polarization (IP) data acquisition and interpretation.. *Journal of Environmental and Engineering Geophysics*. 22 (4), 395. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.2113/JEEG22.4.395

Licenses

Other Conference Presentations / Papers

Woda, Josh, Tao Wen, David O Oakley, Susan L Brantley (2017). *A Geochemical and Structural Geologic Look at Methane Rich Waters Near a Problematic Shale Gas Well*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Del Vecchio, Joanmarie, Roman A DiBiase, Paul R Bierman, Alison Denn (2017). *A Quaternary record of periglacial surface processes preserved in a headwater valley in central Pennsylvania*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Del Vecchio, J., DiBiase, R., Bierman, P., and Denn, A., (2017). *A Quaternary record of periglacial surface processes preserved in a headwater valley in central Pennsylvania*. 2017 AGU Fall Meeting, New Orleans, LA 11-15 Dec.. New Orleans, LA USA. Status = PUBLISHED;

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Li Li*, Peyman Heidari, Lixin Jin, Jennifer Williams, Susan Brantley (2017). *A Reactive Transport Model for Marcellus Shale Weathering*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

West, Nicole, Kirby, Eric, Nyblade, Andrew A., and Brantley, Susan L. (2017). *ASPECT-DEPENDENT FEEDBACKS BETWEEN REGOLITH PRODUCTION AND TRANSPORT AT THE SHALE HILLS CRITICAL ZONE OBSERVATORY*. The Geological Society of America 129th Annual Meeting. Seattle, WA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Napieralski, S.A., V. Macon, S.L. Brantley, and E.E. Roden (2018). *Aerobic microbial lithotrophic oxidation of pyrite at neutral pH*. Goldschmidt 2018 Annual Meeting. Boston, MA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Tang, Qicheng, Li Guo, David M Eissenstat, Henry Lin (2017). *Comparing preferential flow and soil moisture dynamics in two catchments of contrasting lithology*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Dere, Ashlee Laura Denton, Talitha Santini, Sara Parcher, Salome Nyangari, Kimberley Warren (2017). *Critical Zone Evolution Across a Shale Climosequence*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, S.L. and McDowell, W. (2017). *Critical Zone Observatories Town Hall: Platforms for Collaborative Science (presenter with William McDowell)*. American Geophysical Union Fall Meeting. New Orleans, LA Dec. 11-15. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, S.L. (2017). *Developing Online Modules to Teach About Water Quality in Areas of Natural Gas Development Using Hydraulic Fracturing*. 2017 Goldschmidt Conference. Paris, France, August 13-18. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Malik R. (2018). *Do soil communities require living roots for recalcitrant litter decomposition?*. Botany 2018. Rochester, Minnesota. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

F. Reis and S. Brantley (2016). *Effects of the coupling between weathering and erosion on reaction fronts and their transitions (poster),"*. Goldschmidt Conference. Japan, June 26-July 1, 2016. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Richardson, Justin B., Benjamin W. Kumpf, and Louis A. Derry (2018). *Examining the Role of Organic Compounds and Secondary Minerals on Ga/Al Fractionation in the Critical Zone*. Goldschmidt 2018 Annual Meeting. Boston, MA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, S.L. (2017). *Exploring the Effects on Regolith of Fractures, Water Flow, and Biogeochemical Reactions Inside Hills*. 2017 Goldschmidt Conference. Paris, France, August 13-18. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, S.L. (2017). *Exploring the subsurface chemical landscapes where water and biota turn rock into soil*. Departmental Seminar, Vanderbilt University. Nashville, TN, April 14. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, S.L. (2017). *Exploring the subsurface chemical landscapes where water and biota turn rock into soil (Invited Medal Lecture)*. American Chemical Society Meeting,. San Francisco, April 2-6. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Sharkey, Sarah and Timothy S White (2017). *Fostering Collaboration Across the U.S. Critical Zone Observatories Network*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

He, Y. Primka IV, E.J. Tang, Q. Reed, W. Szink, I. (2018). *From Water Cycle to Carbon Cycle: How does soil water impact above- and below-ground tree growth at Shale Hills.*. SSHCZO All Hands Meeting. University Park, PA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

deB Richter, Daniel, Jason Austin, Robert S Anderson, Allan R Bacon, Susan L Brantley, Zachary Brecheisen, Paul A Schroeder, Anna Wade, W. Steven Holbrook, Virginia Marcon, Aaron Thompson (2017). *Gilbert's soil production paradigm applied to a critical zone's fractionation of particle sizes*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Hauser, Emma and Sharon A Billings (2017). *Illuminating pathways of forest nutrient provision: relative release from soil mineral and organic pools*.

American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Wen, Hang and Li Li (2017). *Magnesite Dissolution Rates Across Scales: Role of Spatial Heterogeneity, Equilibrium Lengths, and Reactive Time Scales*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, Susan L. (2018). *Medal: Exploring subsurface geochemical landscapes in the critical zone*. Goldschmidt 2018 Annual Meeting. Boston, MA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

He, Y., K. J. Davis, Y. Shi, D. M. Eissenstat, J. Kaye, M. Kaye (2018). *Observing and Simulating Spatial Variations of Forest C Stocks in Complex Terrain (Poster)*. 5th iLEAPS science conference. Oxford, UK. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

He, Y., K. J. Davis, Y. Shi, D. M. Eissenstat, J. Kaye, M. Kaye, H. Lin, D. Baldwin (2017). *Observing and Simulating Spatial Variations of Forest Carbon Fluxes and Stocks in Complex Terrain (Poster)*. 2017 Gordon Research Conference, Catchment Science: Interactions of Hydrology, Biology & Geochemistry.. Lewiston, ME. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

He, Y., K. J. Davis, Y. Shi, D. M. Eissenstat, J. Kaye, M. Kaye (2018). *Observing and simulating spatial variations of carbon fluxes and stocks in complex terrain*. CZO_LTER_NEON_ISMC cross network workshop. Boulder, CO. Status = ACCEPTED; Acknowledgement of Federal Support = Yes

Herndon, Elizabeth, Grit Steinhoefel, Ashlee Laura Denton Dere, Pamela L Sullivan (2017). *Perennial flow through convergent hillslopes explains chemodynamic solute behavior in a shale headwater catchment*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, S.L. (2017). *Perspectives on CZ Science (Invited Plenary Address)*. National Critical Zone Science Workshop: Current Advances & Future Opportunities. Arlington, VA, June 4-6. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Gu, Xin and Susan Brantley (2017). *Porosity evolution during weathering of Marcellus shale*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Gu, Xin, Peter Heaney, and Susan L. Brantley (2018). *Pyrite oxidation during shale weathering: from catchment – to nanometer – scale*. Goldschmidt 2018 Annual Meeting. Boston, MA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Wayman, Callum Richard, Tess A Russo, Li Li, Brandon Forsythe, Beth Hoagland (2017). *Qualitatively Modeling solute fate and transport across scales in an agricultural catchment with diverse lithology*. American Geophysical Union Annual Fall Conference. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Malik R, Szink I, Primka E, Eissenstat D. (2018). *Root Ecology*. SSHCZO All Hands Meeting. University Park, PA, USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Marcon, Virginia, Beth Hoagland, Xin Gu, Jason Kaye, and Susan Brantley (2018). *Sandstone ridges act as collectors for dust and overlying soil particles over 100 ka timesframes*. Goldschmidt 2018 Annual Meeting. Boston, MA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, Susan L. and Xin Gu (2017). *Shale across Scales from the Depths of Sedimentary Basins to Soil and Water at Earth's Surface (Invited)*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Szink I, Adams T, Orr A, Eissenstat D. (2017). *Slope Position and Soil Lithological Effects on Live Leaf Nitrogen Concentration.*. AGU Annual Fall Meeting. New Orleans, LA, USA.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Szink, Ismaiel, Thomas S Adams, Alexandra S Orr, David M Eissenstat (2017). *Slope position and Soil Lithological Effects on Live Leaf Nitrogen Concentration*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Hasenmueller, Elizabeth A., Pamela L. Sullivan, Julie N. Weitzman, Susan L. Brantley, and Jason P. Kaye (2018). *Soil CO2 Fluxes Through a Temperate Watershed*. Goldschmidt 2018 Annual Meeting. Boston, MA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Guo, Li, Henry Lin, Jonathan Nyquist, Laura Toran, Gregory Mount (2017). *Subsurface Hydrologic Processes Revealed by Time-lapse GPR in Two*

Contrasting Soils in the Shale Hills CZO. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Kim, Hyojin, Xin Gu, Susan Brantley (2017). *Subsurface particle loss during shale weathering can alter soil and rock chemistry*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

White, Timothy S., Adam Wymore, Ashlee Laura Denton Dere, James C Washburne, Adam Hoffman, Martha Conklin (2017). *Teaching climate science within the transdisciplinary framework of Critical Zone science (Invited)*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Marcon, Virginia, Xin Gu, Susan L Brantley (2017). *The Evolution of Porosity During Weathering of Serpentinite and the Creation of Thin Regolith in the Appalachian Piedmont*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Primka IV, E.J. Adams, T. Orr, L. Kaye, J. Eissenstat, D.M. (2018). *Topographic effects on fine root production and soil respiration in the Susquehanna-Shale Hills Critical Zone Observatory (Poster).*. Environmental System Science (ESS) PI Meeting. Potomac, MD. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, S.L. (2017). *Toward a Conceptual Model Relating Reaction Fronts to Water Flow Paths in Hillslopes (Invited)*. Gordon Research Conference - Catchment Science: Interactions of Hydrology, Biology & Geochemistry. Lewiston, ME, June 25-29. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, S.L. (2017). *Toward a conceptual model relating subsurface biogeochemical landscapes to water flow paths in hills*. M. Gordon Wolman Seminar, Johns Hopkins University. Baltimore, MD, September 26. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, S.L. (2017). *Toward a conceptual model relating subsurface biogeochemical landscapes to water flow paths in hills*. Buckley Lecture, University of Illinois. Urbana-Champaign, IL, November 1-3. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Eissenstat, David M. (2018). *Tree roots – How they grow and interact.*. 2018 Forest Health Meeting.. State College, PA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, S.L. (2018). *US CZO Network and Shale Hills CZO (Invited Plenary)*. Watershed Science Collaboration Workshop - DOE-funded workshop. Created Butte, CO Sept 23-25, 2018. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Xiao, Dacheng , Yuning Shi, Beth Hoagland, Joanmarie Del Vecchio, Tess A Russo, Roman A DiBiase, Li Li (2017). *Understanding controls of hydrologic processes across two headwater monolithological catchments using model-data synthesis*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Xiao, D., Shi, Y., Hoagland, B., Del Vecchio, J., Russo, T. A., DiBiase, R. A., Li, L. (2017). *Understanding controls of hydrologic processes across two headwater monolithological catchments using model-data synthesis. (Oral Presentation)*. AGU Fall Meeting 2017. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Xiao, Dacheng, Susan Brantley, Li Li (2017). *Understanding the hydrologic and geochemical control of regolith formation on shale in a hilly landscape*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Shi, Yuning, David M Eissenstat, Yuting He, Kenneth J Davis (2017). *Using a spatially-distributed hydrologic biogeochemistry model with nitrogen transport to study the spatial variation of carbon stocks and fluxes in a Critical Zone Observatory*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brantley, Susan L. (2017). *Using the Critical Zone Observatory Network to Put Geology into Environmental Science (Invited)*. American Geophysical Union Annual Fall Meeting. New Orleans, LA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

HASENMUELLER, Elizabeth A., GU, Xin, WEITZMAN, Julie N., ADAMS, Thomas S., STINCHCOMB, Gary E., EISSENSTAT, David M., DROHAN, Patrick J., BRANTLEY, Susan L. and KAYE, Jason P (2017). *WEATHERING OF ROCK TO REGOLITH: THE ACTIVITY OF DEEP ROOTS IN BEDROCK FRACTURE*. The Geological Society of America 129th Annual Meeting. Seattle, WA USA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Other Products

Educational aids or Curricula.

Online reactive transport modeling course: https://www.e-education.psu.edu/png550/node/829

2017 AGU Session - EP21H.

Brantley was Organizer and Chair (with Carl Steefel, DOE), Oral Session EP21H: Shale: From Fracking to Forest I, American Geophysical Union Fall Meeting, New Orleans, LA, Dec. 11-15, 2017

2017 AGU Session - EP3C.

Brantley was Organizer and Chair (with Carl Steefel, DOE), Poster Session EP3C: Shale: From Fracking to Forest II, American Geophysical Union Fall Meeting, New Orleans, LA, Dec. 11-15, 2017

2017 AGU Session - H43S.

Li Li, Organizer and Chair (with Harry Vereecken, Praveen Kumar, Bhavna Arora) Oral Session - H43S: Modeling the Critical Zone: Integrating Processes and Data Across Disciplines and Scales I.

American Geophysical Union Fall Meeting, New Orleans, LA, Dec. 11-15, 2017

2017 AGU Session - TH25H.

Roman A DiBiase - Organizer and Primary Contact, TownHall Session TH25H: The National Center for Airborne Laser Mapping (NCALM): Future opportunities and community needs in high-resolution topography

American Geophysical Union Fall Meeting, New Orleans, LA, Dec. 11-15, 2017

2017 AGU Session - TH43C.

Timothy S White, Organizer and Primary Contact, TownHall Session - TH43C: Critical Zone Observatories: Platforms for Collaborative Science

Presenters - William H McDowell and Susan L Brantley

American Geophysical Union Fall Meeting, New Orleans, LA, Dec. 11-15, 2017

2017 AGU Session - U11A.

Brantley was Organizer and Chair (with Carl Steefel, DOE), Oral Session U11A: Shale Across All Scales, American Geophysical Union Fall Meeting, New Orleans, LA, Dec. 11-15, 2017

Other Publications

Brantley, S.L. (2017). *Fundamental science issues related to porosity and surface area of subsurface rocks*. DOE Basic Research Needs for the Energy-Water Nexus: New Approaches to Ensure Robust and Secure Energy and Water Systems Workshop Bethesda North Marriott Hotel and Conference Center, Bethesda MD January 4-6, 2017 (Invited Talk). Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Williams, Jennifer Z. (2017). *Making the connection – from the classroom to the field*. A blog post written on TeenShale Network outreach project is available in Adventures in the Critical Zone (http://criticalzone.org/national/blogs/post/making-the-connection-from-the-classroom-to-the-field/). Status = PUBLISHED; Acknowledgement of Federal Support = No

Gold., D., Miller, C., Doden, A., Engelder, T., White, W., Parizek, R., Yoxtheimer, D., Malthur, R., DiBiase, R., Brantley, S., Del Vecchio, J., Dere, A., Eissenstat, D., Guo, L., Kaye, J., Lin, H., Mount, G., West, N., Williams, J., Barnes, H., and Scheetz, B. (2017). *Roadlog for the 82nd annual Field Conference of Pennsylvania Geologists: Recent Geologic Studies & Initiatives in Central Pennsylvania*. Roadlog for the 82nd annual Field Conference of Pennsylvania Geologists: Recent Geologic Studies & Initiatives in Central Pennsylvania. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Patents

Technologies or Techniques

Flux-PIHM-BGC is now included in the open source MM-PIHM project at https://github.com/PSUmodeling/MM-PIHM.

Thesis/Dissertations

Del Vecchio, J.. *A record of coupled hillslope and channel response to Pleistocene periglacial erosion in a sandstone headwater valley, central Pennsylvania*. (2017). The Pennsylvania State University. Acknowledgement of Federal Support = Yes

Gu, Xin. *Characterizing Structure and Geochemistry of Shale Pores by Neutron Scattering*. (2017). The Pennsylvania State University. Acknowledgement of Federal Support = Yes

Denn, A.. *DETECTING LANDSCAPE RESPONSE TO PERTURBATIONS BY CLIMATE AND BASE LEVEL IN CENTRAL PENNSYLVANIA USING IN-SITU 10Be AND 26Al*. (2017). The University of Vermont. Acknowledgement of Federal Support = Yes

Zhang, Y. *FULLY-COUPLED HYDROLOGICAL AND MORPHOLOGICAL PROCESSES FOR MODELING LANDSCAPE EVOLUTION*. (2016). The Pennsylvania State University. Acknowledgement of Federal Support = Yes

Hill, L.Z.. *Lithological controls on soil properties of temperate forest ecosystems in central Pennsylvania*. (2017). The Pennsylvania State University. Acknowledgement of Federal Support = Yes

Bao, Chen. *UNDERSTANDING HYDROLOGICAL AND GEOCHEMICAL CONTROLS ON SOLUTE CONCENTRATIONS AT LARGE SCALE*. (2016). The Pennsylvania State University. Acknowledgement of Federal Support = Yes

Weitzman, Julie. *VARIATION IN SOIL NITROGEN RETENTION ACROSS LAND USES, LANDSCAPES, AND LANDFORMS IN CENTRAL PENNSYLVANIA*. (2016). The Pennsylvania State University. Acknowledgement of Federal Support = Yes

Websites

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Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Brantley, Susan	PD/PI	2
Davis, Kenneth	Co PD/PI	1
Eissenstat, David	Co PD/PI	1
Li, Li	Co PD/PI	3
Bern, Carleton	Co-Investigator	1

Bierman, Paul	Co-Investigator	1
Brubaker, Kristen	Co-Investigator	1
Comas, Xavier	Co-Investigator	1
Dere, Ashlee	Co-Investigator	1
DiBiase, Roman	Co-Investigator	2
Hasenmueller, Elizabeth	Co-Investigator	1
Hayes, Jorden	Co-Investigator	1
Karwan, Diana	Co-Investigator	0
Kaye, Margot	Co-Investigator	1
Kaye, Jason	Co-Investigator	1
Keating, Kristina	Co-Investigator	1
Kirby, Eric	Co-Investigator	1
Lin, Henry	Co-Investigator	1
Liu, Wenjing	Co-Investigator	1
Long, Robert	Co-Investigator	1
Mount, Greg	Co-Investigator	1
Nyquist, Jon	Co-Investigator	1
Perdrial, Julia	Co-Investigator	1
Pett Ridge, Julie	Co-Investigator	1
Richter, Dan	Co-Investigator	1
Shi, Yuning	Co-Investigator	1
Singha, Kamini	Co-Investigator	1
Slater, Lee	Co-Investigator	1
Stottlemyer, Aaron	Co-Investigator	1
Sullivan, Pamela	Co-Investigator	1
West, Nicole	Co-Investigator	1
Caffee, Marc Caffee (PRIME lab, Purdue Univ	Faculty	1
Duncan, Jonathan	Faculty	1
Clarke, Brian	Postdoctoral (scholar, fellow or other postdoctoral position)	0
Gu, Xin	Postdoctoral (scholar, fellow or other postdoctoral position)	1
Adams, Tom	Technician	0
Guo, Li	Staff Scientist (doctoral level)	2
Hidy, Alan	Staff Scientist (doctoral level)	1
Zimmerman, Susan	Staff Scientist (doctoral level)	1
Bao, Chen	Graduate Student (research assistant)	0

Chen, Weile	Graduate Student (research assistant)	1
Del Vecchio, Joanmarie	Graduate Student (research assistant)	5
Denn, Alison	Graduate Student (research assistant)	1
Dillner, Benjamin	Graduate Student (research assistant)	12
Douglas, Baldwin	Graduate Student (research assistant)	0
He, Yuting	Graduate Student (research assistant)	12
Heidari, Peyman	Graduate Student (research assistant)	0
Hill, Lillian	Graduate Student (research assistant)	0
Hoagland, Beth	Graduate Student (research assistant)	1
Hodges, Caitlin	Graduate Student (research assistant)	12
Malik, Rondy	Graduate Student (research assistant)	12
Orr, Alexandra	Graduate Student (research assistant)	0
Osterman, Gordon	Graduate Student (research assistant)	0
Primka, Edward	Graduate Student (research assistant)	1
Reed, Warren	Graduate Student (research assistant)	12
Silverhart, Perri	Graduate Student (research assistant)	6
Szink, Ismaiel	Graduate Student (research assistant)	12
Tang, Qicheng	Graduate Student (research assistant)	12
Wade, Anna	Graduate Student (research assistant)	0
Wayman, Callun	Graduate Student (research assistant)	12
Weitzman, Julie	Graduate Student (research assistant)	0
Xiao, Dacheng	Graduate Student (research assistant)	12
Zarif, Fardous	Graduate Student (research assistant)	0
Forsythe, Brandon	Non-Student Research Assistant	12
Harper, Jeremy	Non-Student Research Assistant	6
Shaphic, Dan	Non-Student Research Assistant	9
Williams, Jennifer	Non-Student Research Assistant	12
Carpenter, Nathan	Undergraduate Student	1
Forgeng, Michael	Undergraduate Student	1
Potter, Joshua	Consultant	1

Full details of individuals who have worked on the project:

Susan L Brantley
Email: brantley@essc.psu.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 2

Contribution to the Project: Principal investigator

Funding Support: NSF

International Collaboration: No
International Travel: Yes, Germany - 0 years, 0 months, 7 days

Kenneth J Davis
Email: kjd10@psu.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: investigator contributing to H7

Funding Support: CZO and Penn State

International Collaboration: No
International Travel: No

David M Eissenstat
Email: dme9@psu.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: lead investigator for H3

Funding Support: Penn State, CZO, DOE

International Collaboration: No
International Travel: No

Li Li
Email: lili@engr.psu.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 3

Contribution to the Project: lead investigator for H5

Funding Support: Penn State University

International Collaboration: No
International Travel: No

Carleton Bern
Email: cbern@usgs.gov
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Advancing the understanding of colloidal transport

Funding Support: USGS

International Collaboration: No
International Travel: No

Paul Bierman
Email: pbierman@uvm.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Geomorphologist/Geochemist - works on Hypothesis 1

Funding Support: University of Vermont and NSF

International Collaboration: No
International Travel: No

Kristen Brubaker
Email: brubaker@hws.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Contributes to H3

Funding Support: Hobart & William Smith Colleges

International Collaboration: No
International Travel: No

Xavier Comas
Email: xcomas@fau.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Hydrogeophysics Specialist

Funding Support: NSF

International Collaboration: No
International Travel: No

Ashlee Dere
Email: ald271@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: shale weathering along transect sites

Funding Support: University of Nebraska, Omaha

International Collaboration: No
International Travel: No

Roman DiBiase
Email: rad22@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 2

Contribution to the Project: Coordinator of geomorphological soils analysis

Funding Support: Penn State and NSF

International Collaboration: No
International Travel: No

Elizabeth Hasenmueller
Email: hasenmuellerea@slu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Hydrochemist - works on Hypothesis 2

Funding Support: St. Louis University

International Collaboration: No

International Travel: No

Jorden Hayes
Email: hayesjo@dickinson.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: New member of advisory board, hydrogeophysics specialist

Funding Support: Dickinson College

International Collaboration: No
International Travel: No

Diana Karwan
Email: dlkarwan@umn.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 0

Contribution to the Project: Cross-CZO Investigator

Funding Support: NSF

International Collaboration: No
International Travel: No

Margot Kaye
Email: mwk12@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Contributes to H3

Funding Support: Penn State

International Collaboration: No
International Travel: No

Jason Kaye
Email: jpk12@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Soil Biogeochemist - works on Hypotheses 2, 3, 5, and 6

Funding Support: Penn State and NSF

International Collaboration: No
International Travel: No

Kristina Keating
Email: kmkeat@andromeda.rutgers.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Contributing collaborator, hydrogeophysics field workshop

Funding Support: Rutgers

International Collaboration: No
International Travel: No

Eric Kirby
Email: eric.kirby@geo.oregonstate.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Geomorphologist - works on Hypothesis 1

Funding Support: Oregon State University

International Collaboration: No
International Travel: No

Henry Lin
Email: hul3@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Hydorpedologist - works on Hypotheses 1, 4, 7, and 8

Funding Support: Penn State and NSF

International Collaboration: No
International Travel: No

Wenjing Liu
Email: wul26@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: collaborative investigator

Funding Support: Chinese Academy of Sciences

International Collaboration: No
International Travel: No

Robert Long
Email: rlong@fs.fed.us
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: collaborating investigator

Funding Support: US Forest Service

International Collaboration: No
International Travel: No

Greg Mount
Email: Gregory.Mount@iup.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Hydrogeophysical specialist, collaborator

Funding Support: IUP

International Collaboration: No
International Travel: No

Jon Nyquist

Email: nyq@temple.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: collaborating investigator

Funding Support: Temple

International Collaboration: No
International Travel: No

Julia Perdrial
Email: Julia.Perdrial@uvm.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: contributing collaborator

Funding Support: University of Vermont

International Collaboration: No
International Travel: No

Julie Pett Ridge
Email: julie.pett-ridge@oregonstate.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Contributing collaborator

Funding Support: Oregon State

International Collaboration: No
International Travel: No

Dan Richter
Email: drichter@duke.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: contributing collaborator

Funding Support: Duke

International Collaboration: No
International Travel: No

Yuning Shi
Email: yshi@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Hydrologist - works on Hypothesis 7 and 8

Funding Support: CZO, Lehigh University

International Collaboration: No
International Travel: No

Kamini Singha
Email: ksingha@mines.edu
Most Senior Project Role: Co-Investigator

Nearest Person Month Worked: 1

Contribution to the Project: Hydrogeologist - works on Hypothesis 1

Funding Support: Colorado School of Mines

International Collaboration: No
International Travel: No

Lee Slater
Email: lslater@andromeda.rutgers.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Collaborative investigator

Funding Support: Rutgers University

International Collaboration: No
International Travel: No

Aaron Stottlemyer
Email: ads175@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: collaborative investigations

Funding Support: Penn State

International Collaboration: No
International Travel: No

Pamela Sullivan
Email: pls21@psu.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Hydrochemist - works on Hypotheses 6 and 9

Funding Support: The University of Kansas

International Collaboration: No
International Travel: No

Nicole West
Email: west2n@cmich.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: geomorphologist - works on Hypothesis 1

Funding Support: Central Michigan University

International Collaboration: No
International Travel: No

Marc Caffee (PRIME lab, Purdue Univ Caffee
Email: mcaffee@purdue.edu
Most Senior Project Role: Faculty
Nearest Person Month Worked: 1

Contribution to the Project: measurement of new cosmogenic nuclides for H1

Funding Support: PRIME lab, Purdue University

International Collaboration: No
International Travel: No

Jonathan Duncan
Email: jxd523@psu.edu
Most Senior Project Role: Faculty
Nearest Person Month Worked: 1

Contribution to the Project: contributed to H6

Funding Support: Penn State

International Collaboration: No
International Travel: No

Brian Clarke
Email: bac43@psu.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 0

Contribution to the Project: Geomorphologist - worked on Hypothesis 1

Funding Support: unknown

International Collaboration: No
International Travel: No

Xin Gu
Email: xug102@psu.edu
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 1

Contribution to the Project: collaborative research

Funding Support: Penn State

International Collaboration: No
International Travel: No

Tom Adams
Email: tsa3@psu.edu
Most Senior Project Role: Technician
Nearest Person Month Worked: 0

Contribution to the Project: Contributes to H3

Funding Support: Penn State and DOE

International Collaboration: No
International Travel: No

Li Guo
Email: lug163@psu.edu
Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: 2

Contribution to the Project: Contributes to H4

Funding Support: NSF

International Collaboration: No
International Travel: No

Alan Hidy
Email: hidy3@llnl.gov
Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: 1

Contribution to the Project: Laboratory Analyst

Funding Support: Lawrence Livermore National Laboratory

International Collaboration: No
International Travel: No

Susan Zimmerman
Email: zimmerman17@llnl.gov
Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: 1

Contribution to the Project: Laboratory Analyst

Funding Support: Lawrence Livermore National Laboratory

International Collaboration: No
International Travel: No

Chen Bao
Email: cub200@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: works on Hypothesis 5

Funding Support: unknown

International Collaboration: No
International Travel: No

Weile Chen
Email: wuc139@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: collaborative research

Funding Support: DOE

International Collaboration: No
International Travel: No

Joanmarie Del Vecchio
Email: jzd5570@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 5

Contribution to the Project: MS student in geomorphology working on H1

Funding Support: CZO

International Collaboration: No
International Travel: No

Alison Denn
Email: adenn@uvm.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: contributing to H1

Funding Support: CZO

International Collaboration: No
International Travel: No

Benjamin Dillner
Email: bmd42@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: contributes to H2

Funding Support: CZO

International Collaboration: No
International Travel: No

Baldwin Douglas
Email: dcb5006@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: collaborative investigations

Funding Support: Penn State

International Collaboration: No
International Travel: No

Yuting He
Email: yzh120@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: works on PIHM and Biome-BGC

Funding Support: CZO

International Collaboration: No
International Travel: Yes, United Kingdom - 0 years, 0 months, 4 days

Peyman Heidari
Email: heidarip@mst.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: collaborator on reactive transport modeling

Funding Support: Missouri University of Science and Technology

International Collaboration: No
International Travel: No

Lillian Hill
Email: lzh157@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: contributing to H2

Funding Support: CZO

International Collaboration: No
International Travel: No

Beth Hoagland
Email: neh137@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: contributing to H6

Funding Support: CZO

International Collaboration: No
International Travel: No

Caitlin Hodges
Email: cah423@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: contributes to H2

Funding Support: CZO

International Collaboration: No
International Travel: No

Rondy Malik
Email: rjm472@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: contributes to H3

Funding Support: CZO and Penn State

International Collaboration: No
International Travel: No

Alexandra Orr
Email: aso124@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: collaborative investigations

Funding Support: Penn State

International Collaboration: No
International Travel: No

Gordon Osterman

Email: gko4@rutgers.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: groundwater geophysics

Funding Support: Rutgers

International Collaboration: No
International Travel: No

Edward Primka
Email: ejp25@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: contributes to H3

Funding Support: CZO, Penn State, and DOE

International Collaboration: No
International Travel: No

Warren Reed
Email: wpr5005@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: Contributes to H3

Funding Support: Penn State

International Collaboration: No
International Travel: No

Perri Silverhart
Email: phs8@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: worked on H1

Funding Support: REU/RET for CZO from NSF

International Collaboration: No
International Travel: No

Ismaiel Szink
Email: ips5062@PSU.EDU
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: Contributes to H3

Funding Support: Penn State and NSF

International Collaboration: No
International Travel: No

Qicheng Tang
Email: qut9@psu.edu
Most Senior Project Role: Graduate Student (research assistant)

Nearest Person Month Worked: 12

Contribution to the Project: contributes to H4

Funding Support: CZO

International Collaboration: No
International Travel: No

Anna Wade
Email: anna.wade@duke.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: collaborating student working with postdoc to learn hydrology sampling techniques in the CZO.

Funding Support: Duke University

International Collaboration: No
International Travel: No

Callun Wayman
Email: crw5269@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: contributed to H6

Funding Support: CZO

International Collaboration: No
International Travel: No

Julie Weitzman
Email: jnw142@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: works on Hypothesis 2

Funding Support: CZO and NSF

International Collaboration: No
International Travel: No

Dacheng Xiao
Email: dzx102@psu.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: contributing to H5 and H8

Funding Support: CZO

International Collaboration: No
International Travel: No

Fardous Zarif
Email: fardous zarif
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 0

Contribution to the Project: collaborator on geophysical methods, specifically electrical resistivity surveys

Funding Support: Rutgers University

International Collaboration: No
International Travel: No

Brandon Forsythe
Email: brf11@psu.edu
Most Senior Project Role: Non-Student Research Assistant
Nearest Person Month Worked: 12

Contribution to the Project: watershed coordinator

Funding Support: CZO

International Collaboration: No
International Travel: No

Jeremy Harper
Email: jph217@psu.edu
Most Senior Project Role: Non-Student Research Assistant
Nearest Person Month Worked: 6

Contribution to the Project: field assistant

Funding Support: CZO

International Collaboration: No
International Travel: No

Dan Shaphic
Email: dms139@psu.edu
Most Senior Project Role: Non-Student Research Assistant
Nearest Person Month Worked: 9

Contribution to the Project: data management

Funding Support: CZO

International Collaboration: No
International Travel: No

Jennifer Williams
Email: jzw126@psu.edu
Most Senior Project Role: Non-Student Research Assistant
Nearest Person Month Worked: 12

Contribution to the Project: Program, Outreach, and Sample Coordinator

Funding Support: CZO

International Collaboration: No
International Travel: No

Nathan Carpenter
Email: ncarpenter@mtech.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: undergraduate thesis on Cole Farm

Funding Support: Penn State and NSF

International Collaboration: No
International Travel: No

Michael Forgeng
Email: mjf5807@psu.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: undergraduate field assistant

Funding Support: CZO

International Collaboration: No
International Travel: No

Joshua Potter
Email: jep189@psu.edu
Most Senior Project Role: Consultant
Nearest Person Month Worked: 1

Contribution to the Project: collaborative outreach

Funding Support: Penn State

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Beijing Normal University	Academic Institution	Beijing, China
Brown University	Academic Institution	Providence, RI
Missouri University of Science and Technology	Academic Institution	Rolla, MO
Ninxia University	Academic Institution	Ningxia, China
Oregon State University	Academic Institution	Corvallis, Oregon
Princeton University	Academic Institution	Princeton, NJ
Rutgers University	Academic Institution	New Brunswick, New Jersey
Saint Louis University	Academic Institution	Saint Louis, MO
State College Area School District	School or School Systems	State College, PA
Technical Univ. of Munich	Academic Institution	Munich, Germany
Temple University	Academic Institution	Philadelphia, PA
UMass-Amherst	Academic Institution	Amherst, MA
CTEMPS	Academic Institution	University of Nevada, Reno
USDA Forest Service	State or Local Government	Corvallis, OR.
USDA-NRCS-NSSC	State or Local Government	Newtown Square, PA

Univ of Kansas	Academic Institution	Lawrence, Kansas
University of Guelph, Canada	Academic Institution	Guelph, ON, Canada
University of Nebraska Omaha	Academic Institution	Omaha, NE
University of Texas @ El Paso	Academic Institution	El Paso, TX
University of Toulouse, France	Academic Institution	Toulouse, France
Chinese Academy of Sciences	Academic Institution	Beijing, China
Colgate University	Academic Institution	Hamilton, NY
Dickinson College	Academic Institution	Carlisle, Pennsylvania
Hollidaysburg Area High School	School or School Systems	Hollidaysburg, PA
Horbart & William Smith Colleges	Academic Institution	Geneva, New York
Indiana University of Pennsylvania	Academic Institution	Indiana, Pennsylvania
Kent State University	Academic Institution	Kent, Ohio

Full details of organizations that have been involved as partners:

Beijing Normal University

Organization Type: Academic Institution
Organization Location: Beijing, China

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Brown University

Organization Type: Academic Institution
Organization Location: Providence, RI

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

CTEMPS

Organization Type: Academic Institution
Organization Location: University of Nevada, Reno

Partner's Contribution to the Project:
Facilities
Collaborative Research

More Detail on Partner and Contribution:

Chinese Academy of Sciences

Organization Type: Academic Institution
Organization Location: Beijing, China

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Colgate University

Organization Type: Academic Institution
Organization Location: Hamilton, NY

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Dickinson College

Organization Type: Academic Institution
Organization Location: Carlisle, Pennsylvania

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Hollidaysburg Area High School

Organization Type: School or School Systems
Organization Location: Hollidaysburg, PA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Horbart & William Smith Colleges

Organization Type: Academic Institution
Organization Location: Geneva, New York

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Indiana University of Pennsylvania

Organization Type: Academic Institution
Organization Location: Indiana, Pennsylvania

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Kent State University

Organization Type: Academic Institution
Organization Location: Kent, Ohio

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Missouri University of Science and Technology

Organization Type: Academic Institution
Organization Location: Rolla, MO

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Ninxia University

Organization Type: Academic Institution
Organization Location: Ningxia, China

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Oregon State University

Organization Type: Academic Institution
Organization Location: Corvallis, Oregon

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Princeton University

Organization Type: Academic Institution
Organization Location: Princeton, NJ

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Rutgers University

Organization Type: Academic Institution
Organization Location: New Brunswick, New Jersey

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Saint Louis University

Organization Type: Academic Institution
Organization Location: Saint Louis, MO

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

State College Area School District

Organization Type: School or School Systems

Organization Location: State College, PA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Technical Univ. of Munich

Organization Type: Academic Institution
Organization Location: Munich, Germany

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Temple University

Organization Type: Academic Institution
Organization Location: Philadelphia, PA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

UMass-Amherst

Organization Type: Academic Institution
Organization Location: Amherst, MA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

USDA Forest Service

Organization Type: State or Local Government
Organization Location: Corvallis, OR.

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

USDA-NRCS-NSSC

Organization Type: State or Local Government
Organization Location: Newtown Square, PA

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

Univ of Kansas

Organization Type: Academic Institution
Organization Location: Lawrence, Kansas

Partner's Contribution to the Project:

Collaborative Research

More Detail on Partner and Contribution:

University of Guelph, Canada

Organization Type: Academic Institution
Organization Location: Guelph, ON, Canada

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

University of Nebraska Omaha

Organization Type: Academic Institution
Organization Location: Omaha, NE

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

University of Texas @ El Paso

Organization Type: Academic Institution
Organization Location: El Paso, TX

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

University of Toulouse, France

Organization Type: Academic Institution
Organization Location: Toulouse, France

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution:

What other collaborators or contacts have been involved?

PA Department of Conservation & Natural Resources - Bureau of Topographic & Geologic Survey

PA Department of Conservation & Natural Resources - Bureau of Forestry

PA Department of Conservation & Natural Resources - State Parks

Centre County Pennsylvania Senior Environmental Corp (CCPaSEC)

David Goerman, Jr. | Water Program Specialist | Department of Environmental Protection

Heather Gall, Ph.D. | Assistant Professor of Agricultural and Biological Engineering | Penn State

Robert Hilton, Ph.D. | Associate Professor of Geosciences | Durham University, UK

Mateja Ogric|Geosciences graduate student| Durham University, UK

Elizabeth Herndon, Ph.D. | Assistant Professor of Geology | Kent State University

Anne Jefferson, Ph.D. | Associate Professor of Geology | Kent State University

Lixin Jin, Ph.D. | Associate Professor of Geology | University of Texas - El Paso

Lin Ma, Ph.D. | Associate Professor of Geology | University of Texas - El Paso

Steven Peters, Ph.D. | Associate Professor of Geology | Lehigh University

Frank Pazzaglia, Ph.D. | Associate Professor of Geology | Lehigh University

Laura Toran, Ph.D. | Professor of Hydrogeology | Temple University

Jordon Hemingway| postdoctoral student | Harvard University

Pam Sullivan | Assistant Prof | Univ of Kansas

Jon Pollak | CUAHSI

Liza Brazil | CUAHSI

Sharon Dykhoff | Dominion Christian School

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Impacts

What is the impact on the development of the principal discipline(s) of the project?

Overall:

We published a paper describing the vision of a future CZO network of observatories and we participated in running the National Critical Zone Science Workshop: Current Advances & Future Opportunities in summer 2017.

The team has developed and is using RT-Flux-PIHM -- the first numerical model capable of modeling hydrological, land surface interactions, and multi-component reactive transport together in one code.

With implementation of instrumentation in our agricultural watershed, we are just about to begin to publish papers probing how agriculture affects CZ processes.

We discovered the importance of transport of clay particles in the subsurface in shale lithologies.

We are starting to show how the understanding of reaction fronts in the subsurface can elucidate hydrologic flow paths.

We have published a water budget, nitrogen budget, carbon budget, and manganese budget for Shale HIlls.

We discovered that belowground biomass can vary with lithology even when aboveground biomass does not.

We are learning and teaching how to assimilate data during modelling -- a technique used extensively in meteorology -- in hydrology and earth system modelling.

Impacts for each hypothesis:

H1. The work at Young Womans Creek provides a key data set for understanding how rock strength modulates landscape response to base-level fall.

H2. The work in all three subcatchments on H2 is testing a simple and robust pore chemistry monitoring approach, and is emphasizing comparisons among catenas. The work could lead to a widely applied strategy to compare pore chemistry across the CZ. Our work is showing the utility of using soil gas chemistry to infer important metabolisms in the soil environment.

H3. The team has improved its understanding of how different tree species of different root morphology and different mycorrhizal types forage for water and nutrients. This information regarding root traits is now being incorporated into Earth System Models to reduce the uncertainty in terrestrial carbon stores and fluxes.

H4. H4 observed that the shale site showed a higher preferential flow frequency at the mid-slope sites and ridge-top site, while at the valley floor the sandstone site had a higher preferential flow frequency. This work indicates that lithology plays an important role in creating different macropore flow patterns, while slope position should also be considered, especially for toe slope positions where the water table is shallower. We proposed a new multiple linear regression method, a multi-index comprehensive evaluation method and a weighted osculating method to enhance our ability to observe the highly dynamic preferential flow. The chance of subsurface flow occurring at larger spatial scale is strongly associated with the precipitation input.

This confirmed the threshold behavior of precipitation in triggering large scale lateral flow in the Shale Hills catchment.

H5. H5 developed and is using RT-Flux-PIHM -- the first numerical model capable of modeling hydrological, land surface interactions, and multi-component reactive transport together in one code. This provides a powerful tool to explore complex process coupling not only for SSHCZO, but also for other CZOs. It can be used for X-CZO model data comparison to derive general principles. We also continued work on the hillslope regolith model. Once developed, this code will also be used at other CZOs.

H6. The H6 team collected stream chemistry and discharge data, and has integrated physical and chemical measurements to locate and characterize groundwater – streamwater interactions, specifically addressing questions about near-subsurface water transport and the observation of multiple "water tables" on hillslopes. Over the next year the team will continue research on simulating solute flux along Shaver's Creek by upscaling mechanistic models from subwatersheds, or developing new approaches using geospatial and statistical methods. Measurements collected at our new farm site are also enabling us to start to understand the broader Shavers Creek watershed, and especially the agricultural component.

H7. H7 is determining the degree to which knowledge of topography, lithology, and soil physical properties are needed to understand watershed carbon-nitrogen-water cycling. We will also identify the observational networks required to characterize carbon stock and fluxes in complex topography. This work moves us towards the objective of a data assimilation system for coupled watershed hydrology and biogeochemistry. This work will ultimately result in an improved understanding of the impact of topography and soil properties on carbon-water-nutrient cycling across the earth's landscape, especially in low-order watersheds. We anticipate that this modeling system and CZO observations can be used to evaluate global model parameterizations of these processes and systems, and to assess the impacts of climate and land-use change on watershed hydrology and biogeochemistry with high resolution and fidelity.

H9. H9 tested the team's first attempt at earthcasting weathering at Shale Hills catchment by using aspect as if it provided a proxy for a future warmer climate. Use of a cascade of models along with the weathering code, WITCH, allowed the team to model weathering on both sides of the Shale Hills catchment. With this work the team began to understand why weathering fluxes are larger on the north side of the catchment, soil porewater chemistry is roughly the same on both sides of the catchment, but the extent of weathering recorded in the soils is greater on the south side of the catchment.

What is the impact on other disciplines?

Overall: The SSHCZO has an excellent track record and organizational plan for development of an integrated CZ model that will be used in many ancillary disciplines.A series of papers have been published describing the modules and their use.

The PIHM modelling family now has a suite of modules that can be used for simulations of different functions at different time scales:

PIHM: hydrology. Duffy et al. Completed
Flux-PIHM: hydrology coupled with land surface interactions. Shi et al. Completed
RT-Flux-PIHM -- Chen Bao and Li Li hydrological, land surface interactions, and multi-component reactive transport
Flux-PIHM-BGC: hydrology coupled with land surface interactions and biogeochemical reactions. Ken Davis and Yuning Shi In Progress
Flux-PIHM-WITCH: hydrology coupled with land surface interactions and weathering. P. Sullivan and Y. Godderis In Progress
PIHM-LE: hydrology coupled with landscape evolution. R. Slingerland and Y. Zhang Paper submitted

Impacts on defense-related science: the CZO's three COSMOS units (installed in each of the three subcatchments) have become of great interest to the US Army. The Army is interested in how to measure soil moisture to be able to predict mud conditions on roads. COSMOS might be a useful way to make such measurements. The Army has begun making wide field measurements to be used to assess utility of COSMOS.

The Pennsylvania Dept of Enviro Protection has reached out to the CZO to help the DEP categorize upland watersheds in terms of vulnerability to perturbations from mining, forest disturbance, shale gas development, road building, etc. The SSHCZO has begun to work with the DEP on this important question and they may provide the CZO funding for this work.

Impacts on other disciplines described per each hypothesis:

H1. H1 has begun developing the use of combined GPR, seismic, and resistivity surveys for geomorphology and this use of these geophysical techniques in this way will be useful for soil science and for characterizing the architecture of the critical zone.

H2. Ecological experimental designs could be impacted if the team's catena monitoring approach proves successful in illuminating key drivers of ecosystem dynamics from a few carefully located sampling points. Evidence that this impact is occurring comes from the Hoagland et al. 2017 paper in which pore water chemistry data from this team led to a new interpretation of Q-C relationships for hydrologists.

H5. The RT-FLUX-PIHM model is cross-disciplinary in its capability of integrating processes important for different disciplines (hydrology and geochemistry). The hillslope regolith model will be integrating hydrology, geochemistry, and geomorphology.

H7. The development of the PIHM family of models has initiated collaboration across all of the disciplines of our CZO project. Our work has also introduced the concept of biogeochemical data assimilation to fields not typically used to utilizing these tools in their research. We hope that the results of this work will also enable high-resolution, high-fidelity simulation of the impacts of climate, environmental chemistry, and land use changes on watershed carbon, nitrogen and water cycles. Our work may inform new treatment of the role of topography in regional to global scale simulations of the terrestrial carbon cycle, such as earth systems models used for climate projections.

H9. By driving WITCH with Flux-PIHM, H9 showed how to incorporate porewater chemistry, soil gas chemistry, hydrology, and land surface interactions together to model weathering.

What is the impact on the development of human resources?

During this year, 22 faculty, 37 graduate students, and ~ 100 undergraduate students have been working or studying at the Susquehanna Shale Hills CZO. The site is acting as a mecca for students and faculty to learn and teach critical zone science. The CZO was chosen as the location for the 2017 annual PA Geological Field Conference. During the conference, 243 Pennsylvania geologists toured the CZO and were introduced to CZ science from ecology to soil science to hydrology to geomorphology.

In addition, a 15 member Chinese delegation of geoscientists chose to spend a week learning of CZ research, field/laboratory techniques, data management, sample storage/archive protocols, and developing ideas for collaborations.

8 water resource extension educators were introduced to CZ processes such as soil moisture dynamics, macropore flow in the subsurface, geochemical weathering of the shale bedrock to shale-derived soils, and the timing and usage of water in the catchment by the vegetation;

4 near-surface geophysics classes from different institutions, along with 5 Chinese scholars engaged in a 1-day resistivity and seismic survey campaign;

17 undergraduates completed GeoPATHS - a 2 week near-surface field experience in the Garner Run catena (11 female participants and 12 under-represented minority participants) - project was led by 7 faculty from 5 institutions and peer-mentored by 4 graudate students (2 female and 2 under-represented minority);

Shale HIlls served as a test bed for the first ever academically-led large scale 3D seismic refraction survey (funded by DOE).

Shale Hills also hosted a team from the **Army Corp Geospatial Research Laboratory Engineer Research and Development Center** which captured leaf area index (LAI) measurements, collected soil cores for chemical analyses, utilized lidar mapping via Leica C10 (tripod mounted) and Geoslam Zeb Revo (hand-held backpack) techniques, and measured soil water content using time-domain reflectometry (TDR) within the Cosmic-ray Soil Moisture Observing System (COSMOS) footprint with the goal to develop and test models a priori that utilize remote sensing to predict landscape characteristics;

Shale Hills CZO also was used by the following Penn State classes: PSU Forestry 475 - Principles of Forest Soils Management, PSU Geoscience 483 - Environmental Geophysics, PSU Geoscience 413 - Techniques in Environmental Geochemisty, PSU Geoscience 203 - Physical Processes in Geology, PSU Soils 405 - Hydropedology, and PSU Soils 597 - Watershed Ecohydrology;

4 AGU Sessions were organized: Oral Session U11A: Shale Across All Scales, Oral Session EP21H: Shale: From Fracking to Forest I, Poster Session EP3C: Shale: From Fracking to Forest II, and H086: Modeling the Critical Zone: Integrating Processes and Data Across Disciplines and Scales.

The CZO seminar series this year included the following presentations, open to anyone on campus at Penn State and broadcast by webinar to all other interested individuals:

August 25th: Dr. Eric Roden, Albert and Alice Weeks Professor of Geosciences at University of Wisconsin-Madison, presents "***Extracellular electron transfer (EET) in the critical zone: biological redox transformation of insoluble Fe-bearing minerals in soil and sedimentary environments***"; September 15th: Dr. Susan L. Brantley, Distinguished Professor of Geosciences and Lead-PI, presents "***State of the CZO***"; October 20th: Dr. Diana Karwan, Assistant Professor of Forest Hydrology, University of Minnesota, presents *"**Short Term Fallout Radionuclides Reveal Sediment Mixing and Transport in the Critical Zone**";* October 30th: Dr. Kathleen Lohse, Associate Professor of Biological Sciences and Director of Reynolds Creek CZO, resents "***Improving prediction of soil carbon and fluxes at the plot to landscape scale***"; November 6th: Dr. Dave Eissenstat, Professor of Woody Plant Physiology, presents "***Strategies of Nutrient Acquisition in Temperate Trees***"; December 4th: Dr. Li Li, Associate Professor of Environmental Engineering, and Dr. Jon Duncan, Assistant Professor of Watershed Hydrology, present "***Models in the CZO***"; January 26th: "***Impact of trees on the CZO***" with contributions from Jill Marshall, Ken Davis, Yuting He, Yuning Shi, and others; February 26th: "***Upscaling the CZO: from Shale Hills to Shaver's Creek and beyond***" with team member contributions; March 30th: Roman DiBiase presents "***CZ interests and proposed research***"; April 23rd: Brandon Forsythe and Dan Shapich discuss "***Field plans and data protocols***"; May 10th– 11th: SSHCZO All-Hands – AGU style mini-symposium, May 10th included 5 oral presentations, the CZO field trip with Ying Fan Reinfelder, 8 faculty, and 18 students/postdocs, and concluded with featured seminar by Ying Fan Reinfelder @ 4:00pm "***Three Hydrologic Depths in the Earth's Critical Zone – Linking Hillslope to Global Processes***", and a student/post-doc dinner with Reinfelder; May 11th included 5 student/postdoc oral presentations, 11 poster presentations, brainstorming for renewal, and networking. The program planner is available http://criticalzone.org/shale-hills/research/annual-activities-shale-hills/. June 7th: CZO Network Postdoctoral Scholar, Adam Wlostowski, presented "***Hydrologic Storage and Partitioning across the CZO Network***"

The SSHCZO enabled science through ***eight seed grants at six other institutions*** (one investigator at Penn State who was not originally funded by our CZO was also funded):

$9,886 – to Dr. Lixin Jin, University of Texas El Paso, "Using carbon isotopes to determine the sources and mass balance of CO2 during shale weathering at Susquehanna Shale Hills Critical Zone Observatory." This funding resulted in one presentation at 2013 AGU Fall Meeting and one journal article published in 2014 Geochimica et Cosmochimica Acta.

$10,464 – to Dr. Jonathan Nyquist and Dr. Laura Toran, Temple University, “Geophysical Prediction of Water Migration along the Soil-Bedrock Interface at the Shale Hills Critical Zone Observatory.” This funding resulted in two presentations, 2013 GSA Annual Meeting and 2014 Northeastern GSA Section Meeting, and one journal article published in 2018 Vadose Zone Journal.

$10,688 – to Dr. Margot Kaye, Penn State, “Filling gaps in the aboveground carbon budget of the SSHO CZO.” This resulted in one Master of Science Thesis and one journal article published in 2017 Canadian Journal of Forest Research.

$9,587 – to Dr. Lin Ma, University of Texas El Paso, “Quantifying regolith formation rates with U-series isotopes along the shale weathering transect within the Susquehanna Shale Hills Critical Zone Observatory.” This resulted in one presentation at 2014 AGU Fall Meeting and one journal article published in 2017 Chemical Geology.

$4,668 – to Dr. Steven Peters and Dr. Frank Pazzaglia, Lehigh University, “Reconciling physical and chemical profiles in the complex soils of the Shale Hills CZO” resulted in training for two early career female Ph.D. graduate students in geochemical techniques and two presentations at NE GSA section meeting in 2014.

$9,902 – to Dr. Elizabeth Herndon, Kent State University, “Investigating inorganic and organic-mediated cation transport from soils to streams” resulted in two presentations, 2015 GSA Fall Meeting and at 2017 AGU Fall Meeting, and one journal article in 2018 Chemical Geology.

$10,000 – to Dr. Carleton Bern, USGS Soil Scientist, “Quantification of mass balance of colloidal material across lithologies and environments” resulted in two presentations, 2017 International Symposium on Applied Isotope Geochemistry and 2016 GSA Fall Meeting, and one journal article in 2018 Chemical Geology.

$19,927 – to Dr. Kristen Brubaker, Hobart William Smith Colleges, “Modeling fine-scale above carbon storage using LiDAR: A comparison across two watersheds” resulted in the training of 2 undergraduate students in ecological field techniques and one journal article published in 2018 Canadian Journal of Forest Research.

What is the impact on physical resources that form infrastructure?

Overall:

Now that instrumentation of the agricultural subcatchment is complete, we have three fully instrumented subcatchments, one on shale, one on sandstone, and one on cultivated calcareous shale. Hydrologic sampling of the entire watershed of Shaver's Creek has been ongoing since fall 2016. A new deep monitoring well was installed in the valley floor of Shale Hills to a depth of 115ft, and six new wells have been installed in Cole Farm. We fixed our eddy flux tower at Shale Hills and we are in the process of fixing the soil gas samplers throughout all three subcatchments.

We also installed three new soil pits with soil moisture probes in Shale Hills subcatchment.

We completed installation of a COSMOS at Cole Farm: this means that we now have COSMOS installed at Shale Hills, Garner Run, and Cole Farm. This physical installation is of great interest to the US Army and they have begun research in the sites because of the COSMOS installation.

What is the impact on institutional resources that form infrastructure?

The CZO research was leveraged to acquire a DOE grant (Brantley, Nyblade) aimed at assessing the use of geophysics to determine subsurface porosity and chemistry.This work is enabling research by postdocs Xin Gu and Natalie Accardo.

The Shale Hills observatory was also used to assess species variation in mycorrhizal root foraging by a Ph.D. student (Weile Chen) working in the Eissenstat lab and funded by NSF BIO Directorate, IOS program.

Our three COSMOS units (installed in each of the three subcatchments) have become of great interest to the US Army. The Army is interested in how to measure soil moisture to be able to predict mud conditions on roads. COSMOS might be a useful way to make such measurements. The Army has begun making wide field measurements to be used to assess utility of COSMOS.

What is the impact on information resources that form infrastructure?

Four new datasets (Sequential filtration of stream and groundwater of the Shale Hills catchment and High-frequency water chemistry of the Shale Hills catchment 2015, 2016, 2017) have been submitted to the EarthChem library and assigned DOIs, all with public release dates of September 2019, bringing the **total EarthChem library contributions from SSHCZO to forty-three.**

The SSHCZO is revising “Precepts for Collaboration,” a guide to best practices for collaborative science at the SSHCZO, for publication.

The tree survey at Shale Hills is available on line (measure DBH on all trees >20cm, record mortality, record recruitment, correct species). As these data are re measured periodically, the dataset will grow and become more valuable.

A user manual is being developed for RT-FLUX-PIHM.

Eddy covariance flux data from a pristine forest shale site (Shale Hills) and agricultural shale site (Cole Farm) are available to the research community.

Shale Hills has been incorporated into the AmeriFlux network, and the EcoStress validation site network.

Data Manager/Cyberspecialist continued to import CZO data into locally-hosted MS SQL Server database, linked to local CZO data portal web site (http://www.czo.psu.edu/data_overview.html). Instrument map on this site was maintained, including adding new instrumentation and data collection sites. The addition of an agricultural sampling site is currently underway. PHP scripts were written to download data via web from this database (e.g., http://www.czo.psu.edu/data_surfflux.html).

Data Manager/Cyberspecialist has uploaded a number of new and/or updated datasets of the following: Land/Atmosphere Fluxes, Soil Gas and Porewater Concentrations, Discharge, Stage, and Water Chemistry, Surface and Groundwater Chemistry, Precipitation and other Meteorology, Ground Penetrating Radar, Colloidal Suspensions, Vegetation (Shrub) Transects, Soil Moisture, Soil Temperature, Soil Electrical Conductivity, Soil Dielectric, Soil Respiration. These new datasets and pre-existing ones are accessible via http://criticalzone.org/shale-hills/data/datasets and http://www.czo.psu.edu/data_overview.html. Time series and other datasets have been imported into locally-hosted SQL Server database, and access pages (e.g.,http://www.czo.psu.edu/data_surfflux.html) created.
Data Manager/Cyberspecialist continued to populate and maintain locally-hosted MS SQL Server database for storage and archiving of local CZO data. Currently there is approximately 206 Gigabytes of data in the database amongst over 100 data tables. It is assumed this database will be maintained beyond the project.

All datasets were summarized in two recent publications: Li et al. in press, Vadose Zone Journal; Brantley et al. in press, Vadose Zone Journal.

What is the impact on technology transfer?

COSMOS is a new instrument that can be used to measure soil moisture across landscapes. The three COSMOS units (installed in each of the three subcatchments) have become of great interest to the US Army. The Army is interested in how to measure soil moisture to be able to predict mud conditions on roads. COSMOS might be a useful way to make such measurements. The Army has begun making wide field measurements to be used to assess utility of COSMOS. We anticipate working closely with the Army into the future.

What is the impact on society beyond science and technology?

The TeenShale water quality outreach project trained 16 high school participants (2017-2018 academic year) in authentic field research in collaboration with Penn State experts. Participants use scientific instruments to measure stream depth and velocity and water quality indicators such as stream temperature, pH, dissolved oxygen, and electrical conductivity. As an inquiry-based project, all aspects from the evolution from ideas and data gathering, to data analysis, comparisons with big data, and science communication are addressed. New this year, the students are applying their skill sets in a nearby watershed to evaluate the impact of an orphaned well on Wallace Run. This year's cohort included one senior, who participated her entire high school career. An article was published in the October 2017 issue of *In The Trenches: ONLINE EXTRA - Bringing the Outdoors In - Application of Hydrogeology Education Tools.*

The CZO team continues collaborations with Shaver's Creek Environmental Center. The CZO has been working with them to implement a CZ Hike at the center and CZ exhibits and CZ instrumentation at the center. Thousands of people visit this center annually.

At least three very large societal problems are related to ongoing work at our CZO. Specifically, many members of the public are worried about hydraulic fracturing and whether the injection of fracking fluids could enter groundwater resources. Will fracking harm groundwater? This can be rephrased as, what is the depth of the critical zone? We are actively working to understand how to model and predict the dept of flow of water in the subsurface.CZO data sharing efforts have helped promote data sharing about water quality in areas of shale gas development (see Science paper published on this topic).

In a second example, the US is seeking a geologic site to safely dispose radioactive waste. This disposal site must sequester the waste from groundwater, must not be eroded or weathered away, must not be easily fractured to allow inlet of new groundwater, and must be safe from human intrusion. All of these societally relevant questions are essentially CZ questions. Will a geologic repository be eroded before the radwaste decays adequately? This can be rephrased as, what is the rate of weathering and erosion in this locality? All of the work we do at the Susquehanna Shale Hills CZO is aimed at understanding these types of questions, although our target area is one watershed in central PA.

In a third example, one of the largest environmental problems in the US is nutrient pollution from nonpoint sources. This is a particular problem in the Susquehanna River Basin and has impacted the largest estuary in the USA, the Chesapeake Bay. The work on Shavers Creek is now quantifying N and P inputs and exports and our upscaling efforts will be used to elucidate issues related to agricultural pollution sources.

The CZO is also actively working to improve models of land-surface processes will inform climate change predictions and climate change impact predictions. These improved predictions are potentially of great value to resource managers from a wide variety of disciplines. No one knows how much of the land surface must be incorporated into earth systems models: with our PIHM suite of models, we are exploring that question.

Other work that has benefited from the CZO:

National Academies of Sciences, Engineering, and Medicine. 2017. *Investigative Strategies for Lead-Source Attribution at Superfund Sites Associated with Mining Activities*. Washington, DC: The National Academies Press. DOI 10.17226/24898 (contributors: Committee on Sources of Lead Contamination at or near Superfund Sites; Board on Environmental Studies and Toxicology; Division on Earth and Life Studies; National Academies of Sciences, Engineering, and Medicine)

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Changes/Problems

Changes in approach and reason for change

After working with SSHCZO for five years, each of Henry Lin's graduate students left his program. In other words, no CZO student chose to remain working with Henry Lin in College of Agricultural Sciences. For example, most recently, grad student Qicheng Tang reported to the CZO PI that he wanted a new advisor. That student is now working with Dave Eissenstat and Jon Duncan. Duncan is a hydrologist and a new Assistant Professor in College of Ag Sci. He is enthused to begin working at the CZO. The work of Qicheng for his dissertation is proceeding well under this new supervision. Henry Lin is welcome to continue working at the CZO (without funded grad students) and he will participate by working (at least) on Qicheng's first paper on soil moisture.

The team also previously reported that the CZO decided not to give out more than the original four seed grants because the grantees were not publishing with the money. In this final year, the CZO was gratified to see that almost all the seed grantees did ultimately publish papers. The papers are summarized elsewhere in this Annual Report. The CZO concluded that the seed grant program was a huge success in that it allowed transferral of NSF dollars from Penn State to other institutions, and, although the timing of publication was somewhat slow, the funding results in extremely high quality work. The seed grant program should be continued.

Actual or Anticipated problems or delays and actions or plans to resolve them

The Shale Hills flux tower was not functioning for a large fraction of the year due to structural problems with the tower, combined with instrument maintenance needs. Those issues are being resolved. We are also replacing some soil gas samplers and sensors in all three subcatchments.

After Tess Russo left Penn State. Susan Brantley supervised her two graduate students, Callum Wayman and Beth Hoagland. Both have done well: Wayman defended his Masters Thesis in early Sept and Hoagland will defend her PhD the first week of October. Hoagland was awarded an NSF Postdoctoral Fellowship and will work at Colorado School of Mines and US Geological Survey.

Some issues remain with respect to Henry Lin and the soil moisture work. Dave Eissenstat and Brantley are working hard to provide the appropriate opportunity for Lin to continue to collaborate and work in the CZO team even if no student wants to work in his program.

Changes that have a significant impact on expenditures

We had to use alternate sources of funds to re drill a well in the valley at Shale Hills because the old wells were collapsing and no NSF funds were available for re drilling. The CZO had to use NSF funds to repair the eddy flux tower at Shale Hills.

The CZO data manager, Dan Shapich, took another job within the university because the CZO could not guarantee him funding after Sept 30 (in other words, before the supplemental funding was received). Dan now consults for the CZO approximately 16 h per week, and the watershed manager, Brandon Forsythe, has picked up the data management activity.

Significant changes in use or care of human subjects

Some surveys are being completed by the high school teachers within TeenShale Network to learn about impacts about that ongoing program. This work has been informed by discussions with IRB through Penn State professor Kathy Brasier.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.

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