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Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	Daniel D Richter

Accomplishments

*** What are the major goals of the project?**

In 2001, Jordan *et al.* of the USA's National Research Council framed a new critical zone science as one of the most compelling and significant research projects for the Earth sciences in the 21st century. The excitement and novelty embodied in this claim spring from the need *and* opportunity for the Earth sciences to advance understanding of how the planet from individual places to regional and global scales is being rapidly transformed by humanity. Slightly modifying a

statement by Prof. Bruno Latour, the individual Earth and ecological sciences *completely overlap* in their scientific study of the contemporary Earth system, and *by disciplinary sciences together in a new critical zone science* we can accelerate scientific understanding of our dynamic planet. The overall goal of Calhoun CZO scientists is to integrate their sciences and scholarships within our observatory, among the nine USA critical zone observatories, and among the many emerging international critical zone observatories as well. The NRC in 2001 and NSF in the years that have followed have not only created but have led a new and growing international movement in Earth systems science (Richter et al., 2018).

More specifically at the Calhoun CZO, our goal is to marshal the Earth and ecological sciences to understand how critical zones as porous-solid structures "from tree-top to bedrock" and as dynamic fluids "from the atmosphere to the deepest aquifers" are being transformed from natural to human-natural systems (Richter and Billings, 2015). We see the Calhoun CZ to share much with the larger physiographic province of the Southern Piedmont and to have three temporal phases in its evolution: a) the Calhoun's *ancient*, deep, and highly weathered natural systems, which on the biogeomorphically stable regoliths of the Calhoun CZO have minimal residence times of several million years (Richter and Markewitz 2001, Bacon et al. 2012, St. Clair et al. 2015, Richter and Billings 2015, Calabrese et al. 2018, Holbrook et al. 2019), ancient landscapes that may yet have surprising stories to tell (Richter et al. 2020); b) the *historic* human-natural CCZO system, that involves the European and African Americans cultivation of cotton and other crops that between about 1800 and the 1930s resulted in some of the most agriculturally eroded landscapes in America (Dialynas et al. 2016, Dialynas et al. 2017, Coughlan et al. 2017); and c) the *contemporary* human-natural system, marked by reforestation of severely eroded soils, gullied hillslopes, and floodplains with deeply incised channels and floodplains that have been buried by meters-deep legacy sediments (Richter et al. 2012, Mobley et al. 2014, Parolari et al. 2018, Chen et al., 2018, Cherkinsky et al. 2018, Ferguson et al. 2019, Wade et al. 2020).

Calhoun research is thus motivated by the growing need to understand and manage Earth's human-natural critical zones "in the face of land use change … to inform strategies for sustaining a wide range of human activities" (from NSF's CZO Program Solicitation, NSF 12-575). Critical zone science compels us to integrate the sciences and broader scholarships within the Calhoun CZO and also within all CZOs.

B. Five specific goals of Calhoun CZO

In this our sixth annual report, we continue to respond to our Virtual Site Visit Review of late 2015 and early 2016, and to suggestions made by Program Manager Yuretich from that time to reorganize our hypotheses and goals. The Calhoun CZO has done so and targets five specific goals: three of which are scientific hypotheses, the fourth to promote CZ education and outreach, and the fifth to stimulate cross-CZO science and education. Each of these is described throughout the annual reports of year three to five (2016, 2017, and 2018).

1. Hypothesis on Hydro-biogeochemical Decoupling and Regeneration of the CZ following Land Degradation. *In CZs altered by land degradation and severe erosion, hydrologic and biogeochemical processes in surficial volumes of CZs become decoupled from those at depth, with system recoveries dependent on re-establishment of macroporosity, hydrologic networks, revegetation and rooting, macroinvertebrate activity, and aggregate formation.*

2. Hypothesis on Erosion-Induced Carbon Dynamics. *Delayed oxidation of eroded soil organic carbon (SOC) buried in alluvial sediments represents a substantial fraction of erosion-induced alterations of soil C cycling.*

3. Hypothesis on Persistence of Alternative States. *CZs altered by land degradation, erosion, gullies, and reductions in infiltration, deep rooting, macroinvertebrates, and aggregate formation are impeded by self-reinforcing feedbacks in re-establishing biological productivity and environmental services.*

4. Education and Outreach Goals. *While our main focus is to facilitate research and educational opportunities for undergraduates at two- and four colleges, the Calhoun CZO actively encourages field trips and reaches out nationally and internationally via a variety of media, materials, and events.*

5. Cross-CZO Goals. *We prioritize and encourage a variety of cross-CZO relationships and participate in new and on-going projects that involve our PIs and student, and Earth, ecosystem, and environmental scientists and scholars, and that promote data- and sample-sharing and circulation of information.*

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

Major Activities: Major Activities:

A. Activities with the five CCZO project goals

1. Hydro-biogeochemical Decoupling and Regeneration of the CZ following Land Degradation

a) Geophysics and Geochemistry. A new manuscript led by Steve Holbrook of WyCEHG and Brantley of PSU and PI Richter was published in 2019, that explicitly integrates geophysics and geochemistry using CCZO's 65-m deep borehole. The new paper directly complements St. Clair et al. (2015) *Science* paper, and will be followed by Richter et al. (2020) in the *Soil Science Society of America Journal* that proposes a critical zone paradigm based on G.K. Gilbert's elegant regolith production expression, being the difference of weathering reactions and transport gains and losses. ***This latter manuscript also unveils a new geologic and geomorphologic history of the Southern Piedmont, the physiographic region of the Calhoun CZO -- i.e., that the widely accepted concept that the Piedmont's regolith derives directly from weathering rock below masks an extensive transport-derived landscape complete with major volumes of colluvium.***

CCZO geochemistry has several working groups within the CCZO. The entire Calhoun CZO team of researchers is especially proud of PI Paul Schroeder of UGA who in August 2018, published a Cambridge University Press book entitled, *Clays in the Critical Zone* (http://criticalzone.org/calhoun/publications/pub/schroeder-2018-clays-in-the-critical-zone/) and in 2019 co-authored a paper on environmental nanoparticles in Science (Hochella et al. 2019). We are also proud of Collaborator Terry Ferguson of Wofford College, who has consistently and faithfully worked to expand the CCZO perspective of transport-derived landscapes in the Piedmont. Terry is leading a second poster on this topic at AGU and will submit a manuscript to a peer-publication in 2020.

b) Land-Use History. Environmental anthropologists continue to assemble the history of changes in the land at the Calhoun CZO A most significant manuscript that associates colonial settlement patterns with first peoples patterns of land use across the Sumter National Forest was published in 2018 in *PLOS One* with the title of "Legacy effects of prehistoric native American niche construction on Euro-American settlement." Historical land records and maps, deed chains, geo-rectified historic aerial photography, historical photographs, and human and agricultural census records continue to be archived for future investigations. GIS data sets continue to be built that include shapefiles, point layers, and topology.

c) Land-Use History's Effects on CZ Structure and Process. Fifteen sites have been intensively instrumented to quantify structure and function of CZs affected by contrasting land use histories: three sites are in uncultivated reference hardwoods that exhibit minimal farming impacts on the belowground systems, three in currently cultivated fields, and nine in old-field pine forests that have experienced 60 to 90 years of forest regrowth following farm abandonment. In the plots, we are log data on soil moisture, temperature, and CO2, and O2 with sensors at 0.5- and 1.5-m. At all 15 of these plots, every three weeks we measure moisture by neutron probe and four gases (CO2, O2, CH4, and N2O) at 0.5, 1.5, 3, 5. and 8.5-m. PI Cherkinsky published the first of a suite of papers in *Radiocarbon in 2018*. New PhD graduate Zach Brecheisen (Duke, 2018) has analyzed nearly five years of these gas data (0-8.5 m depth) and will submit a manuscript for peer-publication in 2020.

Historical land-use effects on geomorphology are also being modeled by PhD-graduate Sara Bonetti and PI Porporato who in 2018 submitted a manuscript to the *Royal Society* (Bonetti et al., submitted). Bonetti has given a number of talks on this

work starting at the 2017 Arlington All-Hands meeting, as well as at AGU, and has moved to a post-doc at ETH-Zurich.

d) Long-term Experimental Watersheds. Measurements of rainfall and streamflow continue on the reinstrumented watersheds that historically operated from the 1940s to the 1960s. Groundwater wells with water sensors continue to operate throughout the Holcombe's Branch catchment. The reinstrumentation of the Calhoun watersheds will allow us to quantify changes in hydrologic responses of eroded and gullied catchments as they have been reforested over nearly eight decades. The historic catchment data are posted on our website. PhD student John Mallard will submit a manuscript in early 2019 to a hydrologic journal.

2. Erosion-Induced Carbon Dynamics

a) Observations. Samples of legacy sediments along the channel banks of Holcombe's Branch were supplemented with an outstanding series of samples along Holcombe's principle tributary, what we call the Old Ray Tributary. The Old Ray channel is newly incised in its lower reach, exposing buried soil profiles over many 10s of meters. We have estimated the organic C contents in these legacy and pre-legacy sediments, both in the 1 to 2-m deep historic sediments and in the Holocene sediments below. A Duke PhD student, Anna Wade, leads this research and the first of her two manuscripts on legacy sediments was accepted by *Geomorphology* for publication in late 2019.

b) Modeling. Previous papers by Dialynas et al. 2016, 2017, were complemented with a paper submitted in 2018 by PI Billings, which simulates processes of burial that affect carbon in alluvial bottomlands. Billings' model, which estimates how C budgets are influenced by depositional environments, has both teaching and research value and is featured in her new paper (Billings et al. 2019).

3. Persistence of Alternative States

Environmental historians and anthropologists and modelers have met during the year, to better understand changing land and human dynamics, work on papers, and to submit a new research proposal to NSF's Coupled Human Systems program. Although PI Porporato and Postdoc Coughlan have both moved to new institutions, they both remain entirely committed to ongoing work at the Calhoun CZO.

4. Education and Outreach Program

Led by PI Kathy O'Neill of Roanoke College, educational and outreach products advanced both the Calhoun CZO and CZ science as a whole. Interactive iBooks use GIS-based maps, images, and videos, based on the Calhoun CZO. O'Neill's new undergraduate CZ science class continues to be taught and is now a core part of the environmental curriculum at Roanoke College. Many CCZO field tours were given in 2019. The Calhoun CZO is used by the REU program in soil science at North Carolina State University. We find people to be captivated by the Calhoun landscape and its history, by Critical Zone science.

5. Cross-CZO Projects

In addition to continued collaboration with WyCEHG scientists (Holbrook et al. 2019), Calhoun PIs and students contribute to many Cross-CZO workshop activities. PhD students have dissertation chapters based on cross-CZO research. We shared our hydrology data with the cross-CZO hydrology project of Adam Wlostowski, for whom we gave an in-depth tour of the Calhoun. Adam gave a seminar and chalk-talk at Duke. Our E&O leader PI O'Neill participates with the National Office and national

E&O team. Our data manager Cook participates with the CZO team of data managers. Kansas PhD student, Emma Hauser, is conducting incubation tests at four different CZO and CZEN observatories, including the Calhoun CZO, in work partially funded by the CZ National Office SAVI program. PI Richter in 2019 gave talks and posters, write papers, and teach classes focused on both Calhoun CZO and on the scientific enterprise of the Earth's critical zone. Richter helped produce a 60-min documentary entitled, "The Education of Bruno Latour: From Critical Zone to the Anthropocene" that was publicly screened in 2019 (https://humanitiesfutures.org/media/the-education-of-bruno-latour-from-the-critical-zone-to-the-anthropocene-unlisted/).

Specific Objectives:

Specific Objectives:

Specific objectives, as have been described in the past, are organized by our five specific project goals.

1. Hydro-biogeochemical Decoupling and Regeneration of the CZ following Land Degradation.

a) Geophysics and Geochemistry. To use advanced geophysics and geochemistry techniques and instrumentation to evaluate the structure and processes of the deep, highly weathered Calhoun CZ.

b) Land-Use History. To geographically coordinate historic and contemporary social, land-use, and land-cover data, including aerial photography and remote sensing data, deed chains, census data, and individual farm records, all to describe, evaluate, and model changes in the Calhoun CZ through time, emphasizing how historic land uses shape the contemporary and future of the land, including its management and human livelihoods.

c) Land-Use History's Effects on CZ Structure and Process. To sample, instrument, and model CZ profiles that have experienced contrasting land-use impacts, all to better understand historical legacies, depth dependencies of processes, and regeneration rates of hydro-biogeochemical systems that couple the surface and the deep subsurface Calhoun CZ.

d) Long-term Experimental Watersheds. To re- and up-instrument the Calhoun historic experimental watersheds and continue precipitation and streamflow records of watersheds as they evolve from eroded gullied watersheds in the 1940s through 1960s to fully reforested contemporary catchments that exist today. Intensive instrumentation will allow us to model the intra- and inter-watershed hydrologic changes in hydrologic response over decadal time scales.

e) Calhoun Long-Term Soil-Ecosystem Experiment (LTSE). To resample soils and trees in 2017, in the LTSE's 60th year following conversion of cotton fields to pine forests. Our specific objectives focus on changes of organic carbon at depth and changes in soil macroporosity and aggregation over the decades. To use an eddy flux tower to monitor CO2, heat, and water fluxes in the midst of our LTSE plots.

2. Erosion-Induced Carbon Dynamics. To model the carbon budget of the Calhoun CZO's Holcombe's Branch watershed from 1800 to the present, and estimate erosional losses from uplands, and burial, storage, and reaccruals on alluvial floodplains that are now inundated with legacy sediments.

3. Persistence of Alternative States. To better understand and model how CZs respond to severe land disturbance that has threatened their resilience and regeneration.

4. Education and Outreach. To develop web-based interactive, educational modules for undergraduates and advanced high school students that illustrate key Critical Zone science concepts, based, in part, on data from the Calhoun CZO; to communicate with local, regional, and national publics about Earth and critical zone science, using a variety of media and formats; and to facilitate research and educational opportunities for undergraduate students at 4-year and 2-year colleges.

5. Cross-CZO Research and Projects. To encourage, develop, and prioritize transformative cross-CZO opportunities for research, sample and data sharing, and other CZ projects. Specifically, to contribute to cross-site modeling, hydrologic analyses, biogeochemistry, forest ecology, flux measurements, pedogenesis, environmental history, systems science, organic carbon cycling, and E&O.

Significant Results: Results are organized by our project's five goals.

1. Hydro-biogeochemical Decoupling and Regeneration of the CZ following Land Degradation.

a) Geophysics and geochemistry of the Calhoun CZ. Our geophysical and geochemical datasets and model results are highly complementary, self-reinforcing, and together enrich understanding of critical zone weathering and the regolith. A high visibility, data-rich paper was published in *Scientific Reports* in this last year (Holbrook et al., 2019). An additional manuscript following directly from our publication in *Science* (St. Clair et al. (2015) was accepted for publication in 2019 for publication in Janurary 2020 in the *Soil Science Society of America Journal*, which unveils a new geologic and geomorphologic history of the Southern Piedmont, in other words that the widely accepted idea of the Piedmont's in-situ regolith masks a much more interesting and transport-derived landscape with major volumes of colluvium now dated by OSL to between 50,000 and 110,000 ybp. This latter submission will be followed by others that describe and evaluate paleo-colluvial burial of organic-rich wetland sediments, even with peat, trunks of trees, and pollen (Ferguson et al., in process), and a new concept with data on the critical zone and soil as clay factories (Richter et al., in process), both to be submitted in 2020. Cooperator Rebecca Lybrand examined fungal-hyphae-rock interactions with nano-scale imaging and described these in two peer-papers in 2019.

b) Land-Use History. History of land-use change continues to be actively studied by CCZO social scientists who have interpreted landscape data to demonstrate that many 19th c. farmers extensively terraced and intimately interacted with the erosion they accelerated as they farmed. This perspective is supported by 1933 aerial photography, contemporary LiDAR imagery, and historical records. A new timeline of forest tree-species conversion has been organized from deed-chain records.

c) Land-Use History's Effects on CZ Structure and Process. Soil CO2 and O2 continue to be monitored to evaluate land use effects on belowground biogeochemistry. Evolution of pore size distributions as affected by land use was successfully model in Pelak and Porporato (2019). The interactive role of topography and land use history was quantified in a paper submitted by PhD student Foroughi et al. (2019).

d) Historic Experimental Watersheds. Time-series data of over 4-years are collected in the historic Calhoun watersheds and data inform explorations of watershed hydrology both within high-gradient, eroded watersheds and within low-gradient legacy sediments that mediate flow from uplands and low-order streams to higher-order streams because floodplains are inundated with 0.5 to >2-m of historic sediment. The data exhibit dynamic seasonally dependent storm responses and high variability in spatial response due to landscape position, soil depth, season, and

antecedent precipitation. Legacy sediments thus often sever connections between low-order and higher-order streams. A hydrological paper will be submitted in early 2020.

e) Calhoun Long-Term Soil-Ecosystem Experiment (LTSE). A CO2, heat, and water flux tower continues to collect data in the Calhoun LTSE (Research site R1P2). The tower is in the midst of the 60-year old field study whose soils were resampled for the 11th time in 2017, when the study of reforestation effects on cultivated soils was 60 years in age. Tower results will enrich the long-term soil sampling data described in many CCZO papers and a book.

2. Erosion-Induced Carbon Dynamics.

a) Observations. Initial estimates of organic carbon stored in legacy sediments of the Holcombe's Branch were made starting in 2016. A senior honors thesis was written with the data. Spectacular buried profiles were discovered and excavated for research and education. Duke PhD student, Anna Wade, led this research in recent years, has given several presentations, and has in 2019 a manuscript accepted for publication in *Geomorphology* on the carbon accumulations of Holcombe's Branch legacy sediments.

b) Modeling. Our previously published results from our spatially-explicit tRIBS model simulations (Dialynas et al. 2016, 2017) can be compared with observed C contents in a manuscript accepted for publication in 2019 by Duke PhD student Anna Wade. Modeling of erosion dynamics was advanced in *Nature Scientific Reports* a publication by Zi et al. (2019).

3. Persistence of Alternative States. We extended a previous formulation of the dynamical system of ecohydrological and human dynamics in agroecosystems at the Calhoun with attention to the history of land use, its land degradations and subsequent reforestation. The group led by PI Porporato at Duke and Princeton has made models spatially explicit to describe the development of agricultural activities starting from more fertile and accessible bottomlands, and then subsequently expanding upland towards hillslopes and ridges. Porporato's group is currently calibrating a model using data obtained by archeological and anthropological research by the UGA group (led by PI Nelson and Postdoc Coughlan). We expect to find mathematically the conditions (possibly indicated by thresholds in the soil biogeochemical variables) leading to the agricultural collapse and abandonment of individual fields to be a function of external pressures induced by the cotton market. We then plan to model spatially the phase of degradation and regeneration with particular attention to the nonlinear interactions between social and ecohydrological processes.

4. Education and Outreach. Led by PI Kathy O'Neill, we have developed educational modules derived from spatial datasets for use with Google Earth, cloud-based formats available at no cost to educators. Undergraduate students were involved in this effort. The Calhoun CZO continues to be affiliated with NSF's REU in Soil Science run by North Carolina State and four full-day or 1.5-day field trips have now been given to ~40 REU undergrads. A new undergraduate course called Critical Zone Science and Management continues to be taught at Roanoke College. The class has a lab and has been developed so that it can be taught at different levels of complexity to be used across a range of institutions and student populations. At the University of Kansas, PI Sharon Billings co-teaches a class with lab entitled "Biogeochemistry in the Critical Zone." In 2019, a book chapter that describes a pedology and a pedostratigraphy for the Anthropocene was published in the 2019 Cambridge University Press book on the Anthropocene (Richter, Billings, and Waters,

2019).

5. Cross-CZO Research and Projects. About a half of the CCZO PIs are involved with cross-CZO research projects. Results across sites include field-based mineral weathering experiments led by our Japanese colleagues, soil microbial and biogeochemistry studies, and hydrologic modeling with PIHM. Redox-related experiments have been conducted in several CZOs and are part of a 2018 Calhoun-Luquillo PhD dissertation. We collaborate with the cross-CZO hydrology project and support cross-site E&O projects including co-authoring a paper in *The Earth Scientist* that describes opportunities for integrating CZ science into environmental science courses at undergraduate and high school levels. Depth-dependent ecologic and genomic attributes of bacterial taxa were examined in a 2019 peer-publication (Brewer et al. 2019). Geophysics and geochemistry data from our 70-m weathering profile has drawn such interest that scientists from other CZOs and WyCEHG have written a geophysics-geochemistry paper (Holbrook et al. 2019).

Key outcomes or Other achievements:

Four other exciting outcomes from across the CCZO include.

1. Collaborations with Wofford College Prof. Terry Ferguson and Prof. Missy Eppes of UNC-Charlotte have led to major discoveries and ongoing investigations of deep paleo-colluvium in the vicinity of the Calhoun CZO, some of which buries 14C-dead organic matter and even peat. We have collected and analyzed samples and are cooperating with Dr. Debra Willard of the USGS who has analyzed pollen to enrich the research. We have four OSL dates from the colluvium that range between 50,000 to 110,000 ybp. In 2020, a paper will be published in the *Soil Science Society of American Journal*, a paper that unveils the beginnings of a new geologic and geomorphologic history of the Southern Piedmont. The widely accepted paradigm that the Piedmont's regolith is residual derived from weathering rock directly below is officially in our cross-hairs. In a 2019 AGU poster and manuscript planned to be submitted in 2020, we will continue to evaluate the Piedmont as a residual- and transport-derived landscape complete with spectacular volumes of paleocolluvium, some of which bury peat, wood, and other organic debris.

2. The establishment and continuation of a German-American "mini-CZO" in Germany, starting with funding from German and non-Calhoun CZO support has produced an interesting data set that contrasts soil gases under oak forest, cultivated fields, and vineyards. Our PhD student, Zach Brecheisen, travelled to the University of Koblenz-Landau (Prof. Hermann Jungkunst) in 2015 and installed moisture and biogeochemical sensors and logging equipment, training German master's students and scientific technicians in data collection. Data loggers monitored gas dynamics of the critical zone to many meters depth, and Jungkunst, Brecheisen, and Richter are analyzing the datasets, will meet at the 2019 AGU meeting in San Francisco.

3. Our USFS scientist colleague on the Calhoun CZO team, Dr. Mac Callaham, has advised a UGA graduate student who graduated in 2018 and successfully wrote a thesis on the effects of historic and contemporary land-uses on soil ecology at the Calhoun CZO. Mac continues to serve as the Director of the Calhoun Experimental Forest and has collaborated with technical assistance throughout our CCZO.

4. The sixth Duke PhD student, Anna Wade, who has been supported by the NSF-IGERT program entitled WISeNet, has worked on the Calhoun CZO and is finishing her final PhD year prior to graduation. The IGERT focuses on environmental sensors, their use and data analysis. Anna is monitoring co-located sensors that produce continuous data on redox potential, oxygen concentrations, soil moisture, temperature, and water level in the legacy sediments of Holcombe's Branch.

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

1. High school student education. At five labs at Duke and University of Georgia, high school students have been included in research. At Roanoke College, K-12 educators participated in science pedagogy meetings at which our E&O PI O'Neill gave presentations about critical zone and environmental science.

2. Undergraduate education. From the beginning of the CCZO, we have focused on undergraduate education for much or most of our E&O. At Roanoke College, Duke, the University of Georgia, and the University of Kansas, and at Duke, undergraduates have been involved with CZ science and the Calhoun CZO. At Roanoke College, this has been most active and PI O'Neill provides opportunities for professional development to undergrads, supporting projects that directly contribute to E&O efforts at the CCZO. Laboratory and classroom activities have been developed by PI O'Neill and tested as part of her new co-taught critical zone science class at Roanoke. PI O'Neill has now supported well over a dozen independent research projects over the life of our project and involved several of these students in presentations and manuscript writing. At Duke, a new interdisciplinary course entitled "Environment in Literature, Law, and Science" is scheduled for its third offering in the Fall of 2020, when we expect about 40 undergraduates and 10 masters students to enroll. The Earth's critical zone is a core concept of the science in the class. About 40 undergraduates in North Carolina State University's REU in Soil Science are each summer given a day- or 1.5-day long field trip in CZ science.

3. Graduate education. At Duke, Georgia Tech, Mississippi State, the University of Georgia, and the University of Kansas, graduate students have been involved in the lifeblood of our CZ science and Calhoun CZO. At Duke, seven PhD students have worked on CZ biogeochemistry, hydrology, geomorphology, and systems modeling. Six have earned support from an NSF IGERT program in wireless and sensor technologies. In their final year, Duke PhD students Anna Wade and John Mallard are having their first papers being accepted and reviewed at peer-review journals. At Georgia Tech, graduate students continue to work in Jingfeng Wang's laboratories with highly talented post-docs and visiting research scientists at the CCZO flux tower, in model development and simulation, and data production, processing, and analysis. At the University of Georgia, graduate students are nearing their graduations, including one who has studied land use effects on soil biogeochemistry. One CCZO student Caitlin Hodges graduated from UGA with a paper published in the Soil Science Society of America Journal (Hodges et al., 2019) and is currently enrolled in CZ science studies at Penn State. At the University of Kansas, two CCZO graduate students are well along in their studies of soil biogeochemistry and in remote sensing and geospatial analysis of landscapes. All of these graduate students are presenting their results and CZ science in a wide variety of forums, from AGU, SSSA, ESA, and to local science, 4-H clubs, and conservation groups. It can be emphasized that many of the 15 Calhoun PIs interact actively with all graduate students across institutions. Graduate-student and faculty teams from across our institutions are publishing papers together in flagship science journals for example, *Water Resources Research*, *JGR*, and EGU's *Biogeoscience* and receiving awards for interdisciplinary training, thanks in part to CCZO's interinstitutional enthusiasm and cooperation. To paraphrase the great geologist Clarence Dutton, the Calhoun CZO is treated as commonstock, a shared research resource and opportunity.

4. Postdoctoral scientists and young professors. At Duke, Georgia Tech, the University of Georgia, and the University of Kansas, postdoctoral scientists have been involved in important ways with our CZ science and the Calhoun CZO. During 2019, Dr. Jay Austin, has completed work at the University of Georgia and at Duke, and moved on to a teaching position. Duke post-doc Anthony Parolari was involved in all aspects of the CZO research and is now at a tenure-track assistant professor position at Marquette University. At UGA, the very productive postdoc Mike Coughlan has moved to Oregon State but remains very much a part of our research community. At the University of Kansas, postdoc Dr. Christoph Lehmeier completed his research duties and has moved on to a lab in Germany.

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

Calhoun CZO research is being published in the leading international science journals, including *Science*, *Water Resources Research*, *Scientific Reports*, *Geophysical Research Letters*, *Global Biogeochemical Cycles*, and *New Phytologist* as examples. We are presenting talks at many colleges and universities to different audiences and programs within universities, and at many scientific conferences (see Products for details). In addition, PIs of the Calhoun CZO explicitly reach out to the Earth sciences, and environmental, engineering, ecological, and environmental humanities communities to explain the details and the need for an integrated critical zone science. More than a dozen examples are given below.

K-12 and undergraduate educators: Presentations have been given at a variety of pedagogy meetings; many of these

presentations have had undergraduate co-authors. PI O'Neill leads these efforts, although other PIs are involved.

Students in Undergraduate and Graduate Schools: Several new classes in critical zone science have now been taught at two of our institutions for several times, at Roanoke College and the University of Kansas. Our PI Billings and O'Neill have developed these classes directly because of their involvement in the CZO program.

Graduate and undergraduate student communities: Many formal and semiformal presentations have been made by and to students across many disciplines, all led by Calhoun CZO graduate and undergraduate students.

Hydrologists: PI Porporato and his students and postdocs continue to disseminate results from their CZ research in a variety of hydrology and modeling forums. His student Salvo Calabrese accepted an assistant professorship at Texas A&M and continues to present his CCZO work at AGU and in AGU journals. PI McGlynn's PhD student is giving two talks at AGU 2019. Even though PI Mukesh Kumar and his students have moved to University of Alabama, they continue to give critical zone based hydrology talks in a number of venues including AGU 2019.

Ecosystem Ecologists & Biogeochemists: PI Richter communicates with scholars in a wide variety of disciplines, but is most interactive with biogeochemistry, soil science, ecology, and ecosystem science. PI Thompson continues to lead novel biogeochemical papers into press that acknowledge support from the CCZO project: on the influence of oxygen on the formation of iron precipitates and their subsequent reactivities toward reductive dissolution; on the influence of the frequency of redox fluctuations on iron-carbon dynamics; on a method of standard addition to identify specific iron phases using Mössbauer approaches with complex soils and sediments; and on iron oxide reactions following a two-year redox fluctuation experiment. PI Billings has expanded her technical geological expertise as a biogeochemist and therefore has greatly expanded her ability to communicate widely.

Earth scientists: We continue to give talks and posters on CZ science and the Calhoun CZO at the meetings of AGU and EGU. Many of us were participants in research proposals to the recent CZNet competition.

Clay mineralogists: PI Schroeder continues with his active outreach to clay mineralogists. Schroeder led the writing of a CZNet proposal that featured clays and clay minerals across a wide gradient of environments.

Stratigraphers: PI Richter continues to work as an appointed member of the International Commission on Stratigraphy's Anthropocene Working Group and authored a chapter in the Cambridge University Press book on the Anthropocene that was published in 2019.

Biogeo-isotopic scientists: PI Cherkinsky led efforts to discuss CZ science at annual meetings such as the Accelerator Mass Spec Conference and Radiocarbon Conference.

Environmental history: PI Nelson advances the interdisciplinary critical zone science as he examines the human-affected legacies of critical zone history at the Calhoun CZO. He discusses the possibility of initiating a discussion on environmental history as a Cross-CZO working group.

Environmental humanities: PI Richter will co-teach a popular Duke class entitled, "Environment in Literature, Law, and Science", for the third time in the fall of 2020. Critical zone science is a key idea of the class and his co-teachers are from the Literature, Law, and English programs at Duke. PI Richter also helped produce a 60-min documentary that features the Calhoun CZO, entitled "The Education of Bruno Latour: From the Critical Zone to the Anthropocene," which was publicly screened at Duke in 2019. In April, PI Richter gave a half-day field trip to about 75 humanities scholars at a three-day workshop on the environmental humanities sponsored by the National Humanities Center.

Geology and environmental science educators (undergraduates and advanced high school): PI O'Neill and her students continue to disseminate materials via presentations at national and regional scientific and pedagogical meetings. O'Neill is focused on building bridges with professors of geology and environmental science at small liberal arts institutions.

International scientists: PIs Schroeder, Markewitz, Billings, Cherkinsky, Porporato, Bras, Wang, and Richter maintain active international relationships that advances CZ science.

Postdoc and graduate student communities: Many formal and informal presentations were given to student groups and organizations by Calhoun CZO students and PIs across many disciplines. An example is the Thursday afternoon Chalk Talk at Duke's River Center, at which a number of presentations have been given by critical zone scientists.

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

A. The next year's plans are organized below using the five specific goals of the CCZO project.

1. Hydro-biogeochemical Decoupling and Regeneration of CZs following Land Degradation

a) Geophysics and Geochemistry. We will continue to collaborate writing papers in this area. In particular, PIs Richter and Schroeder are writing about the major mineralogical dissolutions and transformations exhibited in the 65-m deep core, concentrating on the feldspars and illites and the clay minerals in the full soil-weathering profile. PhD graduate Brecheisen is leading the writing of a paper on soil gas dynamics in nine soil-weathering profiles of 5-m depth, a paper approved by his graduate committee as part of his dissertation. Collaboratory Ferguson is leading a number of the CCZO PIs and students in a detailed investigation of the paleo-colluvium found in a very deep agricultural gully in Pauline, SC. This latter paper will follow from a paper (Richter et al. *Soil Science Society of America Journal*) that will be published in January 2020. We are actively writing research proposals for studies of the close and lagged connections of above and belowground processes and fluxes, proposals that will likely have a clearcutting experiment in which we directly manipulate the interactions of vegetation and deep critical zone weathering reactions.

b) Land-Use History. Environmental anthropologists and historians are continuing to interpret the historical changes in the land at the Calhoun CZO. Historical records, aerial and on-ground photography, and census data are used with contemporary LiDAR images (www.opentopography.org) in geographically explicit models to evaluate human forcings that accelerated and subsequently decelerated soil erosion, the changing species composition of the Southern Piedmont forest, and the relic Holocene hillslopes and landforms that still exist in an otherwise eroded and gullied landscape.

c) Land-Use History's Effects on CZ Structure and Process. Fifteen sites will continue to be monitored to quantify the structure and function of CZs affected by contrasting land use histories: three in uncultivated reference hardwoods that have minimal farming impacts, three in currently and long-cultivated cultivated fields (more than a century of continuous cultivation), and nine sites in old-field pine forests that have grown for 60 to 90 years following farm abandonment. We continue to log continuous soil moisture, temperature, CO2, and O2 data at 0.5- and 1.5-m, and measure soil moisture by neutron probe and two main gases (CO2, O2) down to 8.5-m. We will complete estimates of Ksat down to 4-m in soils and upper saprolites. With regard to C-Fe redox biogeochemistry, data will continue to be analyzed and manuscripts submitted in the coming year. With regard to C turnover within the full CZ, soil enzymes and organic acids will continue to be evaluated, and experiments completed to evaluate the degree to which organic acids and phosphatases generate plant-available P throughout soil weathering profiles of the CCZO. We expect this manuscript to make a large impact on the understanding of the depth dependence of biogeochemical reactions.

d) Long-term Experimental Watersheds. Measurements of rainfall and streamflow will continue on the CCZO-reinstrumented watersheds in addition to water level in an array of groundwater wells. Soil water sensors are instrumented throughout Watershed 4 and within Holcombe's Branch legacy sediments. Analysis of historic strip charts have been completed with the help of the US Geological Survey and USFS Coweeta Hydrologic Lab. At least two manuscripts will be prepared and submitted to journals in the coming year.

e) Calhoun Long-Term Soil-Ecosystem Experiment (LTSE). Soils in the 16 LTSE plots that were resampled and archived in 2017 in year 60 after project initiation. Analyses have begun with a focus on temporal dynamics of structural re-aggregation in the reforested formerly agricultural soils. A preliminary study of lead biogeochemistry will be initiated in 2020, to better quantify accumulation and redistribution of atmospherically deposited lead from combustion of leaded gasoline at this site remote from point sources. We hypothesize that a pulse of low-level lead reached maximum deposition in the 1970s and has slowly leached into the upper 60-cm of very acid mineral soils.

2. Erosion-Induced Carbon Dynamics

Observations. Our manuscript on soil carbon in legacy sediments continues to be assembled, a paper based on the sediment inundation of soil organic carbon (SOC) in Holcombe's Branch. Organic-carbon fractionation studies will be completed to better evaluate the changes in soil organic matter as it lies buried in legacy sediments. We are generally impressed with the coarse textures of legacy sediments of low order floodplain-terraces and the relatively low carbon burial.

A set of five sites along Holcombe's Branch have been instrumented to monitor water level dynamics in legacy sediments

along with redox potential, O2 concentrations, soil moisture, temperature, dissolved organic carbon, to characterize how legacy sediments despite being in receiving areas are generally oxygenated and unable to store much organic carbon.

3. Persistence of Alternative States

PIs Nelson and Porporato, environmental anthropologists and system modelers will continue to interact to better model and simulate the history of changing land and human dynamics. This team in late 2019 submitted a research proposal to NSF's Coupled Human Systems program. The investigators are excited about their continued interactions and their potential to extend their work from the Calhoun to other geographic areas.

4. Education and Outreach Program

We will continue to classroom test educational materials for the Roanoke College undergraduate course in CZ science, and to publish educational materials that integrate interactive maps, text, imagery, and video. We will write and submit a manuscript that argues for the use of the critical zone model in field-based environmental education, a significant pedagogy that is clearly on the wane. In addition, we will publish and improve outreach materials using cloud-based and distributed formats and collaborate on cross-CZO E&O teams coordinated through the National Office, and continue recruitment of undergraduate students, especially from underrepresented groups, to assist with Calhoun research.

5. Cross-CZO Projects

PIs and students are continuing to participate in cross-CZO projects, specifically the soil microbiology (with paper accepted in 2018), biogeochemistry (with paper published in 2018), hydrology (with paper well underway in 2018), and E&O projects. Our data manager continues to participate in the Cross-CZO effort to promote and improve program-wide data management.

B. Plans that support the project at large

1. Biweekly conference calls. Most members of the CCZO are able to participate in biweekly research phone calls.

2. Calhoun CZO-USFS Relations. We continue to work closely with the managers of the Sumter National Forest.

3. Seventh Annual Calhoun Summer Science Meeting. Richter is organizing this year's Summer Science Meeting. We will coordinate some research activities and field trips along with the meeting. We will propose that this event continue into the future, in a tradition that can keep research alive.

4. Calhoun CZO Website. Our website continues to be a focus for our observatory’s growing research, infrastructure, data, models, publications, people, and E&O programs. Early in 2020, we will comprehensively review data sets and begin to review them for a more permanent archive.

5. Data Policy and Management. We will work to implement our accelerated data-sharing policy *within our Observatory*. Our data manager and PI Richter will continue to work to improve design of our data management platform to both analyze, report, and archive CCZO data.

Supporting Files

Filename	Description	Uploaded By	Uploaded On
2019_COMBINED_FINAL - Copy.pdf	Ongoing measurements from 15 Calhoun CZO plots illustrating >4 y of EVI, & 0 to 5-meter deep CO2%, O2%, ARQ, soil moisture, and daily precipitation and temperature in three contrasting and well replicated ecosystems: old hardwoods (never cultivated), cultivated, & old-field 60 to 80 yr old pines.	Daniel Richter	12/06/2019
Holbrook_WS2019 s41598-019-40819-9.pdf	Geophysical and geochemical study of the residual Calhoun weathering zone with Earth scientists from	Daniel Richter	12/06/2019

Filename	Description	Uploaded By	Uploaded On
	across the nation (Holbrook et al. 2019).		
sssaj2019.01.0021 (9).pdf	Soil production and the soil geomorphology legacy of G.K. Gilbert (Richter et al. 2020).	Daniel Richter	12/06/2019
2019 CCZO Supplementary subm.pdf	Supplementary Information for Calhoun CZO, Year 6	Daniel Richter	12/10/2019

Products

Books

Book Chapters

Billings, S.A., Sullivan P.L. (2020). Working across scales to project soil biogeochemical responses to climate. *Multi-scale Biogeochemical Processes in Soil Ecosystems: Critical Reactions and Resilience to Climate Changes (Wiley-IUPAC Series on Biophysico-chemical Processes in Environmental Systems)* 5. Yu Yang, Marco Keiluweit, Nicola Senesi, Baoshan Xing. John Wiley & Sons, Incorporated. . Status = AWAITING_PUBLICATION; Acknowledgement of Federal Support = Yes ; Peer Reviewed = Yes ; ISBN: 1119480345.

Richter, D.deB., S.A. Billings, C. Waters (2019). A pedology and pedostratigraphy for the Anthropocene. *The Anthropocene as a Geological Time Unit (In Chapter 2, Stratigraphic Signatures of the Anthropocene)* Jan Zalasiewicz, Colin Waters, Mark Williams, Colin Summerhayes. Cambridge University Press. Cambridge, UK. 41. Status = PUBLISHED; Acknowledgement of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1017/9781108621359.002.

Snyder, B.A., and M.A. Callaham, Jr. (2019). Soil fauna and their potential responses to warmer soil. *Ecosystem Consequences of Soil Warming: Microbes, Vegetation, Fauna and Soil Biogeochemistry* Mohan, J.E.. Academic Press. London. 279. Status = PUBLISHED; Acknowledgement of Federal Support = No ; Peer Reviewed = Yes ; ISBN: 9780128134931.

Inventions

Journals or Juried Conference Papers

Bartlett, Mark S., Amilcare Porporato, and Lamberto Rondoni (2019). Jump processes with deterministic and stochastic controls. *Physical Review E*. 100 (4), 042133. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1103/PhysRevE.100.042133

Billings SA, Richter D deB, Ziegler SE, Prestegaard K, Wade A. (2019). Distinct contributions of erosional and depositional profiles to land-atmosphere exchange of CO2 in two contrasting forests. *Frontiers in Earth Science*. 7 article 36. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.3389/feart.2019.00036

Bonetti, S., Richter, D. D., and Porporato, A. (2019). The effect of accelerated soil erosion on hillslope morphology. *Earth Surface Processes and Landforms*. . Status = AWAITING_PUBLICATION; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/esp.4694

Bonetti, Sara, Daniel D. Richter, Amilcare Porporato (2019). The effect of accelerated soil erosion on hillslope morphology. *Earth Surface Processes and Landforms*. . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/esp.4694

Brecheisen, Zachary S., Charles W. Cook, Paul R. Heine, and Daniel deB. Richter (2019). Micro-topographic roughness analysis (MTRA) highlights minimally eroded terrain in a landscape severely impacted by historic agriculture. *Remote Sensing of Environment*. 222 78. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed =

Yes ; DOI: 10.1016/j.rse.2018.12.025

Brewer, Tess E., Emma L. Aronson, Keshav Arogyaswamy, Sharon A. Billings, Jon K. Botthoff, Ashley N. Campbell, Nicholas C. Dove, Dawson Fairbanks, Rachel E. Gallery, Stephen C. Hart, Jason Kaye, Gary King, Geoffrey Logan, Kathleen A. Lohse, Mia R. Maltz, Emilio Mayorga, Caitlin O'Neill, Sarah M. Owens, Aaron Packman, Jennifer Pett-Ridge, Alain F. Plante, Daniel D. Richter, Whendee L. Silver, Wendy H. Yang, Noah Fierer (2019). Ecological and genomic attributes of novel bacterial taxa that thrive in subsurface soil horizons. *mBio*. 10 (5), e01318-19. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1128/mBio.01318-19

Calabrese, S., and Porporato, A. (2017). Multiple outflows, spatial components, and nonlinearities in age theory. *Water Resources Research*. 53 (1), 110. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/2016WR019227

Calabrese, Salvatore, and Amilcare Porporato (2019). Impact of ecohydrological fluctuations on iron-redox cycling. *Soil Biology and Biochemistry*. 133 188. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.soilbio.2019.03.013

Coughlan, M.R., D.R. Nelson (2018). Geostatistical analysis of historical contingency and land use footprints in the prehistoric settlement dynamics of the South Carolina Piedmont, North America. *Journal for Archaeological Science*. 107 1. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.jas.2019.04.003

Coughlan, Michael R., and Donald R. Nelson (2018). Influences of Native American land use on the Colonial Euro-American settlement of the South Carolina Piedmont. *PLoS ONE*. 13 (3), e0195036. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1371/journal.pone.0195036

Daly, Edoardo, Salvatore Calabrese, Jun Yin, and Amilcare Porporato (2019). Linking parametric and water-balance models of the Budyko and Turc spaces. *Advances in Water Resources*. 134 103435. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.advwatres.2019.103435

Ehret, U., K. Knuth, R. A. P. Perdigao, and J. Wang (2019). Debates - Does Information Theory provide a new paradigm for Earth Science?: Information Physics. *Water Resour. Res.*. . Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Hajji, I., D. F. Nadeau, B. Music, F. Anctil, and J. Wang (2019). An analysis of water vapor fluxes over a seasonal snowpack using maximum entropy production model. *J. Hydrol.*. . Status = UNDER_REVIEW; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Hochella, Michael F., Jr., David W. Mogk, James Ranville, Irving C. Allen, George W. Luther, Linsey C. Marr, B. Peter McGrail, Mitsu Murayama, Nikolla P. Qafoku, Kevin M. Rosso, Nita Sahai, Paul A. Schroeder, Peter Vikesland, Paul Westerhoff, Yi Yang (2019). Natural, incidental, and engineered nanomaterials and their impacts on the Earth system. *Science*. 363 (6434), eaau8299. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1126/science.aau8299

Hodges, Caitlin, John Mallard, Daniel Markewitz, Diego Barcellos, AaronThompson (2019). Seasonal and spatial variation in the potential for iron reduction in soils of the Southeastern Piedmont of the US. *CATENA*. 180 32. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.catena.2019.03.026

Holbrook, W. Steven, Virginia Marcon, Allan R. Bacon, Susan L. Brantley, Bradley J. Carr, Brady A. Flinchum, Daniel D. Richter, & Clifford S. Riebe (2019). Links between physical and chemical weathering inferred from a 65-m-deep borehole through Earth's critical zone. *Scientific Reports*. 9 Article number 4495. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1038/s41598-019-40819-9

Krapu, Christopher, Mark Borsuk, Mukesh Kumar (2019). Gradient-based inverse estimation for a rainfall-runoff model. *Water Resources Research*. 55 6625. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1029/2018WR024461

Liu, Y., M. Kumar, G. Katul, and A. Porporato (2019). Reduced resilience as an early warning signal of forest mortality.

Nature Climate Change. 9 880. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1038/s41558-019-0583-9

Lybrand, Rebecca A., Jason C. Austin, Jennifer Fedenko, Rachel E. Gallery, Erin Rooney, Paul Schroeder, Dragos G. Zaharescu, and Odeta Qafoku (2019). A coupled microscopy approach to assess the nano-landscape of weathering. *Scientific Reports*. 9 Article number 5377. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1038/s41598-019-41357-0

Mobley, M.L., Y. Yang, R.D. Yanai, K.A. Nelson, A.R. Bacon, P.R. Heine, and D.D. Richter (2019). How to estimate statistically detectable trends in a time series: A study of soil carbon and nutrient concentrations at the Calhoun LTSE. *Soil Science Society of America Journal*. 83 (s1), S133. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.2136/sssaj2018.09

Moon, S., J.T. Perron, S.J. Martel, W.S. Holbrook, and J. St. Clair (2017). A model of three-dimensional topographic stresses with implications for bedrock fractures, surface processes, and landscape evolution. *Journal of Geophysical Research: Earth Surface*. 122 (4), 823. Status = PUBLISHED; Acknowledgment of Federal Support = No ; Peer Reviewed = Yes ; DOI: 10.1002/2016JF004155

Pelak, Norman, and Amilcare Porporato (2019). Dynamic evolution of the soil pore size distribution and its connection to soil management and biogeochemical processes. *Advances in Water Resources*. 131 103384. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1016/j.advwatres.2019.103384

Prasad G.V.R., Culp R., Cherkinsky A. (2019). δ13C correction to AMS data: Values derived from AMS vs IRMS values. *Nuclear Instruments and Methods in Physics Research Section B*. 455 244. Status = PUBLISHED; Acknowledgment of Federal Support = No ; Peer Reviewed = Yes ; DOI: 10.1016/j.nimb.2019.01.034

Richter, D.D., M.C. Eppes, J.C. Austin, A.R. Bacon, S.A. Billings, Z. Brecheisen, T.A. Ferguson, D. Markewitz, J. Pachon, P.A. Schroeder, A.M. Wade (2019). Soil production, regolith evolution, and the soil geomorphology legacy of G.K. Gilbert. *Soil Science Society of America Journal*. . Status = AWAITING_PUBLICATION; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Schroeder, Paul (2016). Clays in the Critical Zone: An Introduction. *Clays and Clay Minerals*. 65 (5), 586. Status = PUBLISHED; Acknowledgment of Federal Support = No ; Peer Reviewed = Yes ; DOI: 10.1346/CCMN.2016.064045

Sohrabi, Mohammad M., Daniele Tonina, Rohan Benjankar, Mukesh Kumar, Patrick Kormos, Danny Marks, Charlie Luce (2019). On the role of spatial resolution on snow estimates using a process-based snow model across a range of climatology and elevation. *Hydrological Processes*. 33 1260. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1002/hyp.13397

Wade, A., D.D. Richter, A. Cherkinsky, C.B. Craft, P.R. Heine (2019). Limited carbon contents of centuries old soils forming in legacy sediment. *Geomorphology*. . Status = ACCEPTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Wade, A.M., D.D. Richter, V.P. Medjbe, A.R. Bacon, P.R. Heine, L.J.T. White, and J.R. Poulsen (2019). Estimates and determinants of stocks of deep soil carbon in Gabon, Central Africa. *Geoderma*. 341 236. Status = PUBLISHED; Acknowledgment of Federal Support = No ; Peer Reviewed = Yes ; DOI: 10.1016/j.geoderma.2019.01.004

Yin, Jun, Salvatore Calabrese, Edoardo Daly, and Amilcare Porporato (2019). The energy side of Budyko: Surface-energy partitioning from hydrological observations. *Geophysical Research Letters*. 46 7456. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1029/2019GL083373

Zi, Tan, Mukesh Kumar, and John Albertson (2019). Intercomparing varied erosion, deposition and transport process representations for simulating sediment yield. *Scientific Reports 9,*. 9 12029. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1038/s41598-019-48405-9

Licenses

Other Conference Presentations / Papers

Qafoku, Odeta, Rebecca A. Lybrand, Vaithiyalingam Shutthanandan, Rachel E. Gallery, Jason C. Austin, Jennifer Fedenko, Erin Rooney, Paul A. Schroeder, Dragos G. Zaharescu (2019). *A Correlative Bimodal Surface Imaging Method to Assess Hyphae-Rock Interactions*. Microscopy & Microanalysis 2019 Meeting. Portland, OR. Status = PUBLISHED; Acknowledgement of Federal Support = No

Wang, J., and Y. Tang (2019). *A Non-gradient Model of Evapotranspiration over Land Surfaces (invited talk)*. AOGS 16th Annual Meeting. Singapore. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Calabrese, Salvatore, and Amilcare Porporato (2018). *A dynamical system approach to soil iron and carbon cycles*. European Geosciences Union General Assembly. Vienna, Austria. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Porporato, Amilcare M., Samantha R Hartzell, Mark S Bartlett (2019). *Agricultural risk management under climate variability: the role of crop diversification*. American Geophysical Union Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Nelson, D.R., M.R. Coughlan, and M. Lonneman (2018). *Anthropogenic drivers and the reconstruction of historical forest cover change in the South Carolina Piedmont ca 1790-1940*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Wade, Anna, Daniel Richter, and Paul Heine (2019). *Atmospheric Vs Geogenic: Using Long-Term Soil Experiments to Delineate between Lead (Pb) Sources in the Southern Piedmont*. ASA-CSSA-SSSA International Annual Meeting. San Antonio, Texas. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Noor, Nadia, Aaron Thompson, Zhe Zhou, Drew E. Latta, Michelle M. Scherer, Alain F. Plante, and Thomas Borch (2019). *Bioavailability of carbon in ferrihydrite-organic matter coprecipitates transformed by Fe (II)-catalyzed recrystalization*. Soil Science Society of America International Soils Meeting. San Diego, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Billings, S.A., Z.S. Brecheisen, A. Cherkinsky, C.W. Cook, C. Lehmeier, D. deB. Richter (2018). *Carbon isotopes reveal signals of the Anthropocene in soil carbon pools deep within the critical zone*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Foroughi, Maryam, Daniel Richter, and Daniel Markewitz (2019). *Dynamics of Soil Phosphorus Fractions over 60 Years of Forest Development*. Soil Science Society of America International Soils Meeting. San Diego, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Calabrese, Salvatore, and Amilcare M. Porporato (2018). *Ecohydrological controls on iron redox fluctuations*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Noor, Nadia, Zhe Zhou, Drew E. Latta, Michelle M. Scherer, Alain F. Plante, Thomas Borch, and Aaron Thompson (2019). *Effect of Reaction Time of Fe (II) with Different C/Fe Ratio Containing Ferrihydrite-Natural Organic Matter Coprecipitate on the Bioavailability of Carbon*. ASA-CSSA-SSSA International Annual Meeting. San Antonio, Texas. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Cannida, Tyler (2019). *Elemental analysis of feldspars from the Mary Lou Quarry in Clinton, SC: Implications for Quantifying Mineral Compositions in the Critical Zone*. CURO Symposium. University of Georgia, Athens, Georgia. Status = PUBLISHED; Acknowledgement of Federal Support = No

Ryland, R., D Radcliffe, A Thompson, and D Markewitz (2019). *Erosional redistribution of surface soil: How has changing depth to the argillic altered hillslope interflow*. Soil Science Society of America International Soils Meeting. San Diego, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Tang, Yao, and Jingfeng Wang (2018). *Evolution of energy, water and carbon cycles due to land-use change at Calhoun Critical Zone*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

O'Neill KP, A Mihalache-O'Keef, E Ackley (2019). *GIS across the curriculum: Pedagogical applications in an undergraduate liberal arts institution*. Virginia Association for Mapping and Land Information Systems (VAMLIS). Harrisonburg, VA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Richter, Daniel deB (2018). *GK Gilbert: A Life in Science for the Commonstock (Invited)*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Richter, Daniel (2019). *How Deep is Soil?*. Soil Science Society of America International Soils Meeting. San Diego, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Thompson, A. (2018). *How ferrous iron oxidation serves to structure iron reduction and other anaerobic processes in redox fluctuating environments (invited presentation)*. Fe Biogeochemistry Workshop. Lech, Austria. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Lybrand, Rebecca, George Dragos Zaharescu, Jason Austin, Swarup China, Rachel E. Gallery, Paul A. Schroeder, Daniel Veghte, and Odeta Qafoku (2019). *Ice Formation and Microbes: A Microscale Perspective on Interactive Biophysical Weathering Agents in the Critical Zone*. ASA-CSSA-SSSA International Annual Meeting. San Antonio, Texas. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Carrera-Martínez, R.R., M.K. Taylor, D. Markewitz, L.A. Sutter, and M.A. Callaham, Jr. (2019). *Influence of earthworms (Oligochaeta: Sparganophilidae) on decomposition of riparian leaf litter*. Society for Freshwater Science annual meeting. Salt Lake City, Utah. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Callaham, M.A., Jr., R.R. Carrera-Martínez, and M.K. Taylor (2019). *Know your water, know your soil, know your worms? – Earthworms and biogeochemistry at the margins of North American freshwater*. Society for Freshwater Science annual meeting. Salt Lake City, Utah. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Nelson, Donald, and Michael Coughlan (2019). *Land use trajectories: an empirical analysis of smallholders and the forest transition in the South Carolina Piedmont*. Society for Applied Anthropology Annual Meeting. Portland, OR. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Barcellos, Diego, Ashley Campbell, Jennifer Pett-Ridge, Aaron Thompson (2019). *Length of Oxygen Exposure during Redox Oscillations Affects Rates of Iron Reduction, Anaerobic Carbon Mineralization, and Methane Emissions*. Soil Science Society of America International Soils Meeting. San Diego, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Zhine, Wang, Aaron Thompson, Lori Sutter, and Markewitz, D. (2018). *Plant phosphorus uptake in a P-limited soil environment*. Warnell School, University of Georgia Graduate Student Symposium. Athens, GA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Kumar, M., Y. Liu, A. Parolari, C.-W. Huang, G.G. Katul, A.M. Porporato (2018). *Potential impacts of climate change on tree mortality risk: Do plant hydraulic traits matter?*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Pachon, Julio C., Daniel Richter, Daniel Markewitz, Aaron Thompson, Anna Wade, Rachel Ryland, and Allan R. Bacon (2019). *Predicting Saturated Hydraulic Conductivity with Rapid Estimates of Soil Microaggregation*. ASA-CSSA-SSSA International Annual Meeting. San Antonio, Texas. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Schroeder, Paul A., Daniel D. Richter, and Jason C. Austin (2019). *Quantification of mixed-layer clays in multiple saturation states using NEWMOD2: Implications for the potassium uplift hypothesis*. EuroClay 2019. Paris, France. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Ferguson, Terry A., Allan R. Bacon, Martha C. Eppes, Daniel D. Richter, Debra A. Willard, Sharon A. Billings, Jason C. Austin, Michelle S. Nelson, Alexander Cherkinsky (2019). *Re-investigation of a colluvially filled valley containing deeply buried organic-rich sediments of pleistocene age, Pauline, South Carolina*. Geological Society of America Southeastern Section Annual Meeting. Charleston, South Carolina. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Wang, J., Y. Tang, and Y. Deng (2018). *Retrieval of Friction Velocity from Sensible Heat Flux Parameterized Using MEP Model over Land Surfaces (invited)*. American Geophysical Union Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Wade, Anna, Daniel Richter (2019). *Saturated but Not Yet Suffocated: Seasonal Oxidation-Reduction Dynamics in Southern Piedmont Floodplains*. ASA-CSSA-SSSA International Annual Meeting. San Antonio, Texas. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Thompson, Aaron (2018). *Short-range-ordered (SRO) iron minerals are dynamic, emergent representations of recent environmental conditions in soils*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Wade, Anna, Daniel Richter, Alex Cherkinsky and Paul Heine (2019). *Soil Carbon Stocks and Soil Moisture Regimes of Historic Sedimentation in the Southern Piedmont*. Soil Science Society of America International Soils Meeting. San Diego, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Wade, Anna, Daniel Richter, Alex Cherkinsky and Paul Heine (2019). *Soil Carbon Stocks and Soil Moisture Regimes of Historic Sedimentation in the Southern Piedmont*. Soil Science Society of America International Soils Meeting. San Diego, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Foroughi, M, and D Markewitz (2018). *Soil Phosphorus distribution in the Calhoun CZO landscape*. Soil Science Society of Georgia annual meeting. Athens, GA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Richter, Daniel (2019). *Soil Production and the Soil Geomorphology Legacy of GK Gilbert*. Soil Science Society of America International Soils Meeting. San Diego, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Richter, Daniel deB. (2018). *Strengthening the biogeosciences in environmental research networks (Invited)*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Liu, Y., M. Kumar, G.G. Katul, A. Parolari, A.M. Porporato, C.-W. Huang, A. Konings (2018). *Synergistic data analytics and physical modeling for improved understanding of vegetation dynamics under climatological stress: a key uncertainty in ecosystem management*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Mallard, J.M., B.L. McGlynn, D.deB. Richter (2018). *Terrain and subsurface influences on runoff generation and storage dynamics in a steep, deep, highly weathered landscape*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Pelak, Norman F., and Amilcare Porporato (2018). *The ecohydrological cost of lawns*. American Geophysical Union Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Ghasemian, S., J. Kastens, S.A. Billings (2019). *The relative sensitivity of forest productivity to landscape position vs microtopography*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Brecheisen, Z.S., D. deB. Richter, C.W. Cook, P. Heine, J. Austin (2018). *Time-series measurements of deep soil profile O2, CO2, soil moisture, and aboveground precipitation highlight differential rooting across landuse history treatments at the Calhoun Critical Zone Observatory*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Hauser, E., D. deB. Richter, S.A. Billings (2018). *Tree carbon investments and soil phosphorus dividends: How do rooting systems maximize P acquisition while being thrifty with their carbon?*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Davis I, KP O'Neill (2019). *Visualizing environmental history and landscape change in the southern Piedmont of South Carolina using Esri Story Maps*. Virginia Association for Mapping and Land Information Systems (VAMLIS). Harrisonburg, VA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Richter, Daniel deB. (2018). *Why the history of geoscience is relevant in the Anthropocene: The case of GK Gilbert*. American Geophysical Union 2018 Fall Meeting. Washington, DC. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Other Products

Other Publications

Patents

Technologies or Techniques

Wang, Jingfeng/Georgia Tech

U.S. Patent Application No. 62/864,655 (provisional)

“Field Measurement of Gas Fluxes Using a Non-Gradient Method”

Filed: June 21, 2019

GTRC Reference No.: 7990

Our Reference No.: GTRC7990PRV

Thesis/Dissertations

Bartlett, Mark Stephan, Jr.. *A Mean Field Approach to Watershed Hydrology (PhD Dissertation)*. (2016). Duke University. Acknowledgement of Federal Support = No

Huang, Shih-Yu. *A modeling study of land surface processes and surface energy budgets using the maximum entropy production theory (PhD Dissertation)*. (2017). Georgia Institute of Technology, Atlanta, Georgia. Acknowledgement of Federal Support = No

Tang, Yao. *An Observational and Modeling Study of the Energy, Water, and Carbon Cycle at Calhoun Critical Zone (PhD Dissertation)*. (2018). Georgia Institute of Technology. Acknowledgement of Federal Support = No

Lonneman, Michael C.. *Eroded Landscapes: Agricultural and Environmental Change in the United States Piedmont, 1790-1860 (M.A. Thesis)*. (2018). University of Georgia, Department of Anthropology. Acknowledgement of Federal Support = No

Liu, Yanlan. *Impacts of Climate Variation and Change on Hydrologic and Vegetation Dynamics (PhD dissertation)*. (2019). Duke University. Acknowledgement of Federal Support = No

Min, Kyungjin. *Temperature responses of microbial soil organic matter decomposition and associated respiration at various scales, ranging from exo-enzymes to populations and communities (PhD Dissertation)*. (2017). University of Kansas. Acknowledgement of Federal Support = No

Websites

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Richter, Daniel	PD/PI	6
Kumar, Mukesh	Co PD/PI	9

Name	Most Senior Project Role	Nearest Person Month Worked
McGlynn, Brian	Co PD/PI	1
Palmroth, Sari	Co PD/PI	0
Porporato, Amilcare	Co PD/PI	2
Billings, Sharon	Co-Investigator	4
Bras, Rafael	Co-Investigator	1
Callaham, Mac	Co-Investigator	1
Cherkinsky, Alexander	Co-Investigator	1
Markewitz, Daniel	Co-Investigator	2
Nelson, Donald	Co-Investigator	1
O'Neill, Katherine	Co-Investigator	3
Schroeder, Paul	Co-Investigator	2
Thompson, Aaron	Co-Investigator	2
Wang, Jingfeng	Co-Investigator	1
Bacon, Allan	Faculty	0
Austin, Jason	Postdoctoral (scholar, fellow or other postdoctoral position)	6
Brecheisen, Zachary	Postdoctoral (scholar, fellow or other postdoctoral position)	1
Chapman, Gregg	Technician	1
Cook, Charles	Technician	12
Heine, Paul	Technician	10
Martin, Melissa	Technician	8
Taylor, Melanie	Technician	1
Bastola, Satish	Staff Scientist (doctoral level)	3

Name	Most Senior Project Role	Nearest Person Month Worked
Sutter, Lori	Staff Scientist (doctoral level)	4
Calabrese, Salvatore	Graduate Student (research assistant)	9
Demir, Huseyin	Graduate Student (research assistant)	1
Fackrell, Laura	Graduate Student (research assistant)	1
Foroughi, Maryam	Graduate Student (research assistant)	12
Ghasemian, Soudeh	Graduate Student (research assistant)	5
Hallemeier, Jon	Graduate Student (research assistant)	9
Hauser, Emma	Graduate Student (research assistant)	4
Jing, Weiqiang	Graduate Student (research assistant)	3
Jordan, Bear	Graduate Student (research assistant)	2
Liu, Yanlan	Graduate Student (research assistant)	12
Mallard, John	Graduate Student (research assistant)	9
Noor, Nadia	Graduate Student (research assistant)	3
Steiner, Peter	Graduate Student (research assistant)	1
Tang, Yao	Graduate Student (research assistant)	6
Ubiali, Bruno	Graduate Student (research assistant)	3
Wade, Anna	Graduate Student (research assistant)	4
Wang, Zhine	Graduate Student (research assistant)	12
Zhu, Modi	Graduate Student (research assistant)	12
Ardington, Emma	Undergraduate Student	1
Boyd, Jonathan	Undergraduate Student	3
Cannida, Tyler	Undergraduate Student	1
Davis, Isaac	Undergraduate Student	1

Name	Most Senior Project Role	Nearest Person Month Worked
Lang, Kyler	Undergraduate Student	2
Ryang, Junmo	Undergraduate Student	2
Sanders, Sophia	Undergraduate Student	1
Thedford, Joshua	Undergraduate Student	1
Whalen, Bridgette	Undergraduate Student	3
White, Dexter	Undergraduate Student	1

Full details of individuals who have worked on the project:

Daniel D Richter
Email: drichter@duke.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 6

Contribution to the Project: Richter is lead on two publications and a contributor to many others that are in review or in press. He mentors two Duke PhD students on the project as well as lab and field technical staff. Richter is responsible for all aspects of the project at Duke and sub-contracted to the University of Kansas, Princeton, University of Georgia, Georgia Tech, and Roanoke College.

Funding Support: Duke University

International Collaboration: No
International Travel: No

Mukesh Kumar
Email: mukesh.kumar@duke.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 9

Contribution to the Project: Advised Yanlan Liu. Gave invited talks at several national and international venues. Wrote project report/ papers.

Funding Support: NSF CAREER

International Collaboration: No
International Travel: No

Brian L McGlynn
Email: brian.mcglynn@duke.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: McGlynn has provided guidance and collaboration on watershed hydrology field research including installation of stream gauging stations, nested well networks, precipitation gauges, and soil water content monitoring stations. Additionally he has supported management and analysis of collected and historic data

along with serving as a contact to facilitate implementation of CUAHSI's data model for the CCZO hydrologic data. He continues to integrate findings at the CCZO satellite location in Duke Forest with the larger CCZO project.

Funding Support: Duke University

International Collaboration: No
International Travel: No

Sari Palmroth
Email: sari.palmroth@duke.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 0

Contribution to the Project: None

Funding Support: None

International Collaboration: No
International Travel: No

Amilcare Michele Porporato
Email: aporpora@princeton.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 2

Contribution to the Project: Leading efforts on modeling of clay and land degradation dynamics by the Princeton group.

Funding Support: NSF-FESD and Princeton Carbon mitigation Initiative

International Collaboration: No
International Travel: No

Sharon A Billings
Email: sharon.billings@ku.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 4

Contribution to the Project: Billings was lead on two publications and a contributor to several others that are in review or in press. She mentored two grad students on the project as well as multiple undergraduates who are funded via this and other projects, but who all contribute to lab progress. Billings is responsible for all aspects of the project sub-contracted to the University of Kansas.

Funding Support: University of Kansas

International Collaboration: Yes, Switzerland
International Travel: No

Rafael Bras
Email: rlbras@gatech.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Dr. Bras serves as the co-PI of GT team supervising all team members and coordinating

collaborations of research and education activities. Given his extensive expertise and experience, Dr. Bras worked on the eco-hydrological recovery theme through design of field experiment, model development and simulation.

Funding Support: This award only.

International Collaboration: No
International Travel: No

Mac Aaron Callaham
Email: mcallaham@fs.fed.us
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Identification of invertebrates collected from CCZO sites; co-advisement of graduate student working on CCZO projects.

Funding Support: USDA Forest Service, Center for Forest Disturbance Science

International Collaboration: No
International Travel: No

Alexander Cherkinsky
Email: acherkin@uga.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: The sample collection and analyses for 14C and d13C composition of soil organic matter to estimate the turn over rates on the sites with different land use history.

Funding Support: Center for Applied Isotope Studies, University of Georgia

International Collaboration: No
International Travel: No

Daniel Markewitz
Email: dmarke@uga.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 2

Contribution to the Project: Field work, professional mentoring.

Funding Support: This award only.

International Collaboration: No
International Travel: No

Donald R Nelson
Email: dnelson@uga.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Responsible for activities in the human-CZO theme and contributes to interdisciplinary modeling activities. Contributed to data collection, overseeing graduate work, and professional mentoring

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Funding Support: NSF

International Collaboration: No
International Travel: No

Katherine P O'Neill
Email: oneill@roanoke.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 3

Contribution to the Project: Education and outreach. CCZO Executive Committee member.

Funding Support: Roanoke College Environmental Studies program

International Collaboration: No
International Travel: No

Paul A Schroeder
Email: schroe@uga.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 2

Contribution to the Project: Field work, professional mentoring, planning of international symposium.

Funding Support: TUBITAK (Scientific and Technological Research Council of Turkey)

International Collaboration: Yes, Turkey
International Travel: Yes, Turkey - 0 years, 0 months, 13 days

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Aaron Thompson
Email: aaront@uga.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 2

Contribution to the Project: Overseeeing graduate student and postdoctoral research. Field soil collection and analysis.

Funding Support: University of Georgia

International Collaboration: No
International Travel: No

Jingfeng Wang
Email: jingfeng.wang@ce.gatech.edu
Most Senior Project Role: Co-Investigator
Nearest Person Month Worked: 1

Contribution to the Project: Dr. Wang serves as the lead co-PI of GT team responsible for daily operation of research and education activities. Dr. Wang focused on the eco-hydrological recovery theme for the test of the Eco-hydrological Recovery Hypothesis (H1) through design of field experiment, model development/simulation, and data processing and archiving.

Funding Support: This award only.

International Collaboration: No
International Travel: No

Allan R Bacon
Email: allan.bacon@ufl.edu
Most Senior Project Role: Faculty
Nearest Person Month Worked: 0

Contribution to the Project: Assisted with particle size analysis and manuscript preparation/submission related to several papers.

Funding Support: University of Florida

International Collaboration: No
International Travel: No

Jason C Austin
Email: jayc.austin@gmail.com
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 6

Contribution to the Project: Field work, X-ray diffraction, stable isotope sample collection and analysis, undergrad student mentoring.

Funding Support: This award only.

International Collaboration: No
International Travel: No

Zachary S Brecheisen
Email: zbrecheisen@gmail.com
Most Senior Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
Nearest Person Month Worked: 1

Contribution to the Project: Geospatial analysis, soil and tree coring, plot mapping, soil gas monitoring.

Funding Support: Purdue University

International Collaboration: No
International Travel: No

Gregg Chapman
Email: gchapman@fs.fed.us
Most Senior Project Role: Technician
Nearest Person Month Worked: 1

Contribution to the Project: Gregg assists with soil gas measurements, earthworm surveys, and soil sampling.

Funding Support: USDA Forest Service

International Collaboration: No
International Travel: No

Charles W Cook
Email: cwcook@duke.edu
Most Senior Project Role: Technician
Nearest Person Month Worked: 12

Contribution to the Project: Field lab manager in charge of field construction, operations, sample collection, and data management for diverse field experiments at the Calhoun CZO.

Funding Support: This project only.

International Collaboration: No
International Travel: No

Paul Heine
Email: pheine@duke.edu
Most Senior Project Role: Technician
Nearest Person Month Worked: 10

Contribution to the Project: Field, laboratory, and data contributions.

Funding Support: This award only.

International Collaboration: No
International Travel: No

Melissa Martin
Email: Melissa.martin25@uga.edu
Most Senior Project Role: Technician
Nearest Person Month Worked: 8

Contribution to the Project: Field and laboratory research training

Funding Support: University of Georgia

International Collaboration: No
International Travel: No

Melanie K Taylor
Email: melaniekaytaylor@gmail.com
Most Senior Project Role: Technician
Nearest Person Month Worked: 1

Contribution to the Project: Melanie works with Mac Callaham and provided assistance with set up, sample processing, sample analysis and preliminary data analysis of a laboratory study that was part of Roberto Carrera-Martinez's thesis work.

Funding Support: USDA Forest Service

International Collaboration: No
International Travel: No

Satish Bastola
Email: satish.bastola@ce.gatech.edu

Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: 3

Contribution to the Project: Model development and simulation of the effects of soil erosion and deposition on the carbon cycle.

Funding Support: This award only.

International Collaboration: No
International Travel: No

Lori A Sutter
Email: lsutter@uga.edu
Most Senior Project Role: Staff Scientist (doctoral level)
Nearest Person Month Worked: 4

Contribution to the Project: Laboratory management, field work, professional mentoring.

Funding Support: This award only.

International Collaboration: No
International Travel: No

Salvatore Calabrese
Email: salvatore.calabrese@princeton.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 9

Contribution to the Project: Modeling of clay formation and accumulation and land degradation dynamics.

Funding Support: Princeton Carbon mitigation Initiative

International Collaboration: No
International Travel: No

Huseyin Demir
Email: huseyindemir@uga.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: Graduate research assistant

Funding Support: TUBITAK

International Collaboration: Yes, Turkey
International Travel: Yes, Turkey - 0 years, 0 months, 13 days

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Laura Fackrell
Email: lauraelf@uga.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: Graduate research assistant

Funding Support: University of Georgia

International Collaboration: No
International Travel: No

Maryam Foroughi
Email: mforoughi@uga.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: Field and laboratory research, water chemistry.

Funding Support: This award only

International Collaboration: No
International Travel: No

Soudeh Ghasemian
Email: soudeh.ghasemian@gmail.com
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 5

Contribution to the Project: Ghasemian is working on the Calhoun project to understand how past erosion and topography can influence forest productivity.

Funding Support: University of Kansas teaching assistantship.

International Collaboration: No
International Travel: No

Jon Hallemeier
Email: jhalleme@uga.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 9

Contribution to the Project: Data collection, organization

Funding Support: This award only

International Collaboration: No
International Travel: No

Emma Hauser
Email: emhauser@ku.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 4

Contribution to the Project: Hauser is being trained on laboratory equipment to become adept at multiple biogeochemical assays, including inorganic N and phosphate soil extractions and quantification, exo-enzyme assays, and microbial biomass assays.

Funding Support: University of Kansas teaching assistantship

International Collaboration: No

International Travel: No

Weiqiang Jing
Email: jasonjing@gatech.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Field experiment, model simulation and data analysis (H1).

Funding Support: This award only.

International Collaboration: No
International Travel: No

Bear Jordan
Email: bearjordan@gmail.com
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 2

Contribution to the Project: Masters research on the geology of the Calhoun

Funding Support: University of Georgia

International Collaboration: No
International Travel: No

Yanlan Liu
Email: yanlan.liu@duke.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: Evaluating early warning signals of forest mortality.

Funding Support: Duke University teaching assistantship

International Collaboration: No
International Travel: No

John McDevitt Mallard
Email: john.mallard@duke.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 9

Contribution to the Project: Ongoing installation of sensor network; field hydrologic measurements; hydrologic data acquisition and analysis; assembling and writing manuscripts.

Funding Support: Duke University teaching stipend

International Collaboration: No
International Travel: No

Nadia Noor
Email: nadia.noor25@uga.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Laboratory research contributing measurements of iron reducing populations in the Big Dig soils

Funding Support: University of Georgia and other NSF

International Collaboration: No
International Travel: No

Peter Steiner
Email: psteiner@uga.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 1

Contribution to the Project: Working with Paul Schroeder on analyzing soil samples.

Funding Support: University of Georgia

International Collaboration: No
International Travel: No

Yao Tang
Email: tangyao1208@gatech.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 6

Contribution to the Project: Constructing the two flux towers. Retrieving and processing historical hydrometeorological data and modeling gas fluxes (stream-flow and rainfall)(H1).

Funding Support: This award only.

International Collaboration: No
International Travel: No

Bruno Ubiali
Email: Bruno.ubiali@uga.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Data collection, organization

Funding Support: This award only.

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: 4

Contribution to the Project: Wade has continued ongoing research in Holcombe's Branch by installing soil moisture sensors, oxygen and carbon dioxide gas sensors, and redox sensors. Wade is also measuring the long-term soil experiment plots for historic deposition of lead (Pb), and has been trained on the ICP-MS at Duke for analysis of samples.

Funding Support: Duke University and Forest History Society

International Collaboration: No
International Travel: No

Zhine Wang
Email: ZhineWang@uga.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: Field and laboratory research on determining P availability from clay vs saprolite

Funding Support: University of Georgia

International Collaboration: No
International Travel: No

Modi Zhu
Email: modizhu@gatech.edu
Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 12

Contribution to the Project: Field experiment, model simulation and data analysis (H1).

Funding Support: This award only

International Collaboration: No
International Travel: No

Emma Ardington
Email: eca47061@uga.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Worked on techniques to quantify carbon stability in soils.

Funding Support: University of Georgia

International Collaboration: No
International Travel: No

Jonathan Boyd
Email: jonathangboyd@ku.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3

Contribution to the Project: Assisted Hauser with lab and greenhouse work.

Funding Support: This award and another funded grant.

International Collaboration: No
International Travel: No

Tyler Cannida
Email: tyler.cannida25@uga.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Undergraduate research assistant

Funding Support: University of Georgia

International Collaboration: No
International Travel: No

Isaac Davis
Email: isdavis@mail.roanoke.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Maps as drivers of colonization and land cover change in the southern Piedmont of South Carolina (Educational module developed for StoryMaps).

Funding Support: None

International Collaboration: No
International Travel: No

Kyler Lang
Email: kyler_lang@ku.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 2

Contribution to the Project: Analyzed root abundance data from Duke Farm, compared KS grassland and Duke Farm root data to Calhoun

Funding Support: Funded via another grant, University of Kansas

International Collaboration: No
International Travel: No

Junmo Ryang
Email: junmo.ryang@duke.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 2

Contribution to the Project: Assisted with analysis of Holcombe's Branch legacy sediments. Wrote Python program to merge two datasets.

Funding Support: None

International Collaboration: No

International Travel: No

Sophia Sanders
Email: scs51899@uga.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Undergraduate research assistant

Funding Support: University of Georgia

International Collaboration: No
International Travel: No

Joshua Thedford
Email: jbt25373@uga.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: Worked on techniques to quantify carbon stability in soils.

Funding Support: University of Georgia

International Collaboration: No
International Travel: No

Bridgette Whalen
Email: bcwhalen@mail.roanoke.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 3

Contribution to the Project: Development of Esri Story Maps in support of education and outreach

Funding Support: NSF and Roanoke College

International Collaboration: No
International Travel: No

Dexter White
Email: dewhite@ku.edu
Most Senior Project Role: Undergraduate Student
Nearest Person Month Worked: 1

Contribution to the Project: White works with the portable XRF and helps Hauser with litter incubations.

Funding Support: This award and University of Kansas undergraduate scholarship

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location

Name	Type of Partner Organization	Location
Anthropocene Working Group	Other Nonprofits	Various
Coweeta Hydrologic Lab	Other Organizations (foreign or domestic)	Otto, NC
Franklin Humanities Institute	Academic Institution	Duke University
NSF-REU in Soil Science (North Carolina State Univ)	Academic Institution	Calhoun CZO & Duke Forest
Rose Hill Plantation State Historic Site and SC State Parks	State or Local Government	Union and Columbia, SC
South Carolina State Parks	State or Local Government	Columbia, SC
Sumter National Forest, Enoree District	Other Organizations (foreign or domestic)	Union and Whitmire, SC
USFS Southern Research Station	Other Organizations (foreign or domestic)	Athens, GA
Wofford College	Academic Institution	Spartanburg, SC
WyCEHG: Wyoming Cent Environmental Hydrology & Geophysics	Academic Institution	University of Wyoming

Full details of organizations that have been involved as partners:

Anthropocene Working Group

Organization Type: Other Nonprofits
Organization Location: Various

Partner's Contribution to the Project:
Other: Platform for advancing critical zone science

More Detail on Partner and Contribution: The relations of the proposed Anthropocene and critical zone science are many and to date relatively little explored.

Coweeta Hydrologic Lab

Organization Type: Other Organizations (foreign or domestic)
Organization Location: Otto, NC

Partner's Contribution to the Project:
In-Kind Support
Facilities
Collaborative Research

More Detail on Partner and Contribution: Training given to PhD student for a summer's work (2015) digitizing historic strip chart data. Coweeta hydrologists provided some oversight as well of the progress to the work.

Franklin Humanities Institute

Organization Type: Academic Institution
Organization Location: Duke University

Partner's Contribution to the Project:
Financial support
In-Kind Support
Facilities
Collaborative Research

More Detail on Partner and Contribution: FHI co-sponsored a 2-day visit to the Calhoun by Bruno Latour, widely renowned philosopher of science. FHI entirely sponsored lunch for about 100 scholars at a high-visibility public event we called "The Critical Zone Education of Bruno Latour." A professional videographer was assigned to the two day visit to the Calhoun and is in the final stages of video creation. FHI has also provided an office for PI Richter on his Fall 2016 sabbatical.

NSF-REU in Soil Science (North Carolina State Univ)

Organization Type: Academic Institution
Organization Location: Calhoun CZO & Duke Forest

Partner's Contribution to the Project:
Personnel Exchanges

More Detail on Partner and Contribution: The Calhoun CZO is an affiliate of the NCSU REU Program in Soil Science, whose director is Prof. Josh Heitman. For the second of three years, we have given a whole day field trip in Critical Zone science to about a dozen high potential students. In both years, by days end they have been very intrigued and excited by the experience.

Rose Hill Plantation State Historic Site and SC State Parks

Organization Type: State or Local Government
Organization Location: Union and Columbia, SC

Partner's Contribution to the Project:
In-Kind Support
Facilities

More Detail on Partner and Contribution: The South Carolina State Park Service issued the CCZO a research permit on the grounds of the Rose Hill Plantation State Historic Site and have interests in our work with the old

hardwood forest to the north of the Gist home and in exploring the seriously gullied old fields of the Gist plantation. In 2016, our CZO has agreed to help the SC State Parks with a reinterpretation of Rose Hill, a long-term project that will be led by the University of South Carolina.

South Carolina State Parks

Organization Type: State or Local Government
Organization Location: Columbia, SC

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: Our project's LiDAR-derived data and our interpretation of geomorphological features and human-land impacts are being shared with local Park employees and with the State Park system itself, all to enrich the understanding of the remarkable history of South Carolina. We have encouraged the SC State Park system in reinterpreting Rose Hill Historic Site and to professionally interview and record conversations senior citizens who were born and lived in Rose Hill when it was abandoned, and to support archaeological work at the site.

Sumter National Forest, Enoree District

Organization Type: Other Organizations (foreign or domestic)
Organization Location: Union and Whitmire, SC

Partner's Contribution to the Project:
In-Kind Support
Facilities

More Detail on Partner and Contribution: The USDA Forest Service is responsible for managing research activities on the Calhoun Experimental Forest and in 2014 began the permitting of research activities that were contained in 30-page Research Plan. In 2015 we gave a half-day tour to two prominent USFS managers.

USFS Southern Research Station

Organization Type: Other Organizations (foreign or domestic)
Organization Location: Athens, GA

Partner's Contribution to the Project:
In-Kind Support

More Detail on Partner and Contribution: Dr. Mac Callaham participates in our observatory as a soil biologist

Wofford College

Organization Type: Academic Institution
Organization Location: Spartanburg, SC

Partner's Contribution to the Project:
In-Kind Support
Facilities
Collaborative Research

More Detail on Partner and Contribution: Led by Prof. Terry Ferguson but solidly supported by Prof. John Lane and Kay Savage, Wofford has been a base of consistent support throughout our CZO project. They have brought their

students to the Calhoun on field trips and had a major impact on the development of science among many Calzones. Given that the Calhoun CZO is <30 miles from Spartanburg, Wofford is well positioned in its proximity to benefit from ongoing research at the Calhoun.

WyCEHG: Wyoming Cent Environmental Hydrology & Geophysics

Organization Type: Academic Institution
Organization Location: University of Wyoming

Partner's Contribution to the Project:
In-Kind Support

More Detail on Partner and Contribution: Collaboration on geophysical measurements and modeling with 2nd and 3rd visits to Calhoun in 2016. Writing a 2016 research proposal for a Calhoun drilling research.

What other collaborators or contacts have been involved?

Hermann Jungkunst, University of Koblenz-Landau

Impacts

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

The principal fields of scholarship at the Calhoun CZO are geology and geomorphology; geophysics, geochemistry, pedology, and biogeochemistry; hydrology and ecohydrology; ecology and ecosystem science; environmental history and anthropology; Earth science education; Earth systems science; and straddling all of the above, environmental modeling. Though ambitious, the combination and integration of disciplines represented in the work of the 15 PIs, their students and collaborators, ensure that research planning, techniques, results, and interpretations impact all principle fields of the Calhoun CZO.

Many of the data collected have been novel and invaluable:

a) the high resolution LiDAR-DEM data from the Calhoun CZO flight in July 2014 and the super-high resolution ground-return data from the flight in Feb 2016, b) the geophysics data sets obtained from WyCEHG instruments deployed in Calhoun's Geophysics Weeks I and II in April 2014 and February 2016; c) the time-series observations of CZ metabolism (gas concentration data that began in 2015 down to 8.5-m depth and that will continue into 2020) - See Attached Figure; d) the spatially explicit models using information from archeology, geo-historical records from maps and aerial photography, geospatial soils data, LiDAR data, dendrochronology, and environmental history; and e) the historic and contemporary experimental catchment precipitation and discharge data (1948-1962, 2014-present). The full value of these data will be realized when they circulate among all the Earth and ecosystem scientists, as well as environmental historians and anthropologists. Our work aims to identify and quantify the depths and persistence of legacies of human alterations of landscapes. Using field sites from profiles and plots to small catchments and whole landscapes, lab experiments, and models, we work across temporal and spatial scales of complexity. NSF is investing in critical zone science to integrate the Earth sciences and scholarships, something widely recognized to be transformative but still rarely practiced. We believe this is happening at the Calhoun CZO.

Our project's E&O efforts strive to use our specific CZ developments to create new approaches for teaching Earth and environmental sciences at the undergraduate level. Calhoun's program in E&O reaches a much wider audience than undergrads and includes advanced high school students, graduate students, K-12 teachers, and the general public. The pedagogy of the Critical Zone is new and has the potential to contribute greatly to the development of new teaching approaches, with regards to interdisciplinary earth sciences, coupled human and natural systems, and the environmental sciences.

What follows is a sample of how our PIs have seen their work's impact on "the principal disciplines of the project", with quotations taken from our PI's annual reports this year and in the past, all with only slight rewording.

- My learning and fascination with the Earth sciences has accelerated more in these last four years than in any time in my professional life.
- Our models of coupled weathering and ecohydrologic dynamics and related theoretical analyses offer insight into the coupling of hydrology, biogeochemistry, and ecology. The models may be used to assess nutrient availability to plants and soil degradation.
- Our work helps identify and quantify the depth and persistence of historic human alterations of landscapes and CZs. By having field and laboratory components to the research, we work across temporal scales and scales of complexity. These approaches help reveal patterns of land use history's impact on biogeochemistry and the mechanisms driving them.
- We develop ground-based tools, i.e., EMI, resistivity, and NIRS, through a digital soil mapping framework that helps us parameterize ecohydrological and biogeochemical models with much greater spatial intensity.
- We advance understanding of social, political, and cultural dimensions of human forcings of the CZ, and are particularly interested in understanding the complexity and legacy of these forcings of the CZ.
- The portable gas sampling and analyzer system I designed can be patented and further developed for much broader utility.
- My multilayered geo-pdf maps allow non-GIS researchers and the public to explore and understand the CZ like never before.
- Understanding and quantifying hydrologic interactions with sediment transport and soil organic dynamics is one of the highlights of our research. Process-based models, developed and implemented in this project, are advantageous over empirical approaches as they represent physical theory and hydrologic processes in data-scarce, spatially heterogeneous terrains.
- Educational materials contribute to new pedological approaches in the Earth and environmental sciences. The pedagogy of the CZ is new and has the potential to transform teaching, especially with regards to interdisciplinary Earth sciences, coupled human and natural systems, and the environmental sciences.

What is the impact on other disciplines?

One of the most exciting and potentially fruitful aspects of critical zone science is its capacity to span the disciplines and marshal scientists with disciplinary skills and perspectives to interact in new and important ways. The CZOs are ambitious integrative projects and are in the act of creating a new Earth science as an *inter-discipline*.

This interdisciplinary vision is articulated directly in the 2001 NRC report led by Thomas Jordan, Gail Ashley, and others; it is articulated indirectly by the growing number of CZOs that are being established internationally on all continents (Giardino and Houser 2015). At the Calhoun CZO, it is not only the Earth scientists who are enthused by the interdisciplinarity of the challenges we face, but also our humanity's scholar, an environmental historian, has expressed his enthusiasm and amazement as well, saying: "Environmental history is a relatively new field of history and for all of its growth and impact, only with my involvement in the CZO have I become convinced that environmental scientists see that a fully human-historical perspective to their environmental sciences is necessary."

In keeping with the interdisciplinary nature of critical zone science, the educational and outreach materials developed as part of this project are explicitly interdisciplinary, with elements that cut across the natural sciences (e.g., soils, hydrology, geology, ecology, modeling), the social sciences (e.g., anthropology, land use, land management and policy) and the humanities (e.g., environmental history). The incorporation of critical zone science as an integrating theme in the interdisciplinary environmental educational program at Roanoke College and University of Kansas and other colleges and universities is new but it has the potential to impact educational practices broadly.

A quote from an annual report from one of our environmental engineers, "the theory of age and residence time of Earth's integrated surface systems is of great interest not only to hydrology and geophysics but to chemical engineering, population dynamics, and statistical and fluid mechanics."

The CCZO PIs are excited by the interactions between the integrative CZ science and traditional academic disciplines.

What is the impact on the development of human resources?

This is partly described in the general responses about project personnel.

The Calhoun CZO has 15 PIs based at six universities and colleges as well as the USDA Forest Service. These institutions and PIs involve a very large number of students from many backgrounds, students from high schools to graduate schools to post-docs who are heading in many directions. These are detailed and quantified in other parts of our annual report.

The Calhoun CZO held its sixth all-hands science meeting in 2019 ("Calhoun Summer Science Days"), with multiple presentations and discussions. We have also held all-hands calls-to-work at the CCZO such as our three “Calhoun Geophysics Weeks”, in which a wide variety of students (including underrepresented students) were invited to assemble at the Calhoun to help scientists from WyCEHG who have travelled from Wyoming to work at the Calhoun. In 2016-17, we hosted two “Calhoun BigDigs”, efforts to attract a variety of students and scientists to work together on deep hand-coring to install gas reservoirs to 5 and 8.5-m depth and to sample backhoe-excavated soil and saprolite pits across sites with contrasting land-use histories. We are working with Dr. Justin Richardson (of University of Massachusettes) on two research projects that involve rare earth elements in the Calhoun CZO's 70-m deep core. In the past, many or most of the assembled scientists camp together, which leads to science discussions late into the evenings. We are constructively demanding on our scientists and scholars, but most experience not only the hard work but also the intense joy of scientific investigation.

Educational and outreach from our Calhoun project targets mainly students and teachers at small 4-year and 2-year collegiate institutions. Representation of the Earth sciences at these institutions is typically low-level compared to many research universities. Providing educational opportunities in the Earth sciences within these collegiate communities directly “enhances development of human resources in Earth sciences.” Curricular materials are largely consistent with Next Generation Science Standards and may be adapted for use in advanced high school courses (AP Environmental Science).

What is the impact on physical resources that form infrastructure?

The Calhoun CZO leverages nearly 75 years of research (1947 to present) of land, vegetation, and water at the USFS Calhoun Experimental Forest, a landscape of long and on-going scientific interest due to the serious impacts of about 150 years of agricultural use, mainly for cotton, from about 1800 to 1950. While the USDA Forest Service initiated the Calhoun research program in 1947, in 1962 the USFS dismantled all scientific infrastructure at the Calhoun Experimental Forest, despite 15 years of highly productive research by soil, ecology, and hydrology scientists (Richter et al. 2014). Fortunately, two USFS researchers kept working at two field experiments from 1962 to 1989, when they invited PI Richter and soon after PI Markewitz to join them at the Calhoun. Richter has marshalled nearly continuous financial support from the National Science Foundation (Biological and Geosciences Directorates), several USDA research programs, and the Andrew Mellon, Wallace, and Trent Foundations to keep the Calhoun’s long-term experiments alive and productive.

With the support of our CZ colleagues, we have significantly re- and up-instrumented hydrologic and biogeochemical investigations all across the Calhoun CZO. Not only have we re-instrumented historic experimental catchments, but we have significantly up-instrumented the Calhoun watersheds with intensive and highly sophisticated hydrologic instrumentation. An inverted flux tower is constructed and collecting data from above and deep belowground data streams aimed to quantify legacies of land-use impacts on critical zone hydrology, geomorphology, biology, and biogeochemistry. While the USFS recognized the special values of the Calhoun Experimental Forest, they were institutionally unable to provide funding. Thus, NSF’s CZO program has been able to build upon an unusually strong research base and reconstitute a research site that would otherwise have dwindled or even been completely lost except to the literature.

What is the impact on institutional resources that form infrastructure?

The Calhoun CZO unites and strengthens our diverse institutions in many ways. The institutions include a small undergraduate college (Roanoke), land-grant universities (Mississippi State and University of Georgia), an EPSCoR university (Kansas), large public research universities (Kansas, UGA, Georgia Tech, and Mississippi State), and a private research university (Duke).

Within each institution, PIs and students are based at a variety of departments (e.g., History, Geology, Engineering, Environmental Sciences and Policy, Anthropology, Biology, and Earth Sciences). We use this diversity to contribute to the

project at large. For example, in the fall of 2013, PI Aaron Thompson organized a set of web-based CZ science seminars among the PIs and their students. While the science was useful and interesting for certain, this activity was also a study of contrasting academic cultures as well. Throughout our project, we have held a teleconference call every other week.

Perhaps the most remarkable example of CZO impact on institutions is at Roanoke College, a small 4-year liberal arts college and home to the Calhoun's E&O program. At Roanoke, PI O'Neill has affected with her colleagues a redesign of the interdisciplinary Environmental Studies curriculum with Earth's Critical Zone as one of the organizing themes. All three of the introductory courses in Roanoke's Environmental Studies curriculum (Environmental Science, Environment and Society, and Environment and Culture) address different perspectives of the Earth's critical zone. In addition to a new upper-level course in Critical Zone Science and Management, Critical Zone concepts will be woven throughout the curriculum. This new curriculum has been put in place and starting in 2017 and continuing to the present (2019), the core course that features the CZ and the environment continues to be offered to many hundreds of students!

These programmatic changes at Roanoke have been documented in an article for *The Earth Scientist* (cross-CZO effort) and has been disseminated in presentations to provide a model for other institutions.

What is the impact on information resources that form infrastructure?

In addition to constantly circulating email, discussions by telephone, Skype, Zoom, and WebEx, we use two websites for project management and communication, CZEN.ORG and CRITICALZONE.ORG. While the CZEN.ORG site was an initial repository for proposals, data sets, figures, miscellaneous documents, and communications among Calhoun PIs, the Calhoun CZO investigators have moved to a Google-based system of communications, including Calhoun CZO Google Maps, Calendar, Docs, and Sheets that share writing, maps, sampling locations, and to facilitate general communications. Calhoun staff (Will Cook, Paul Heine) update and build the Calhoun website on CRITICALZONE.ORG. Many data sets are uploaded, and we have recently modified our data policy to speed this process which we see as important to enhancing scientific integration within the project.

What is the impact on technology transfer?

Technology transfer is both research and education based.

The visit of WyCEHG scientists during Calhoun's three Geophysics Weeks (one in 2014, two in 2016) has greatly stimulated to our geophysics expertise within the CZO. Our CCZO PIs with geophysics equipment and experience (Markewitz and Schroeder) developed collegial relationships with WyCEHG scientists and have worked with a University of Wyoming graduate student who investigated GPR data from the Calhoun landscape. During the first WyCEHG visit, our colleagues in regional offices of the National Resource Conservation Service (NRCS) visited the Calhoun and were extremely interested in WyCEHG instrumentation and data analysis. These same NRCS personnel attended our Big Dig! Fall 2016, at which they formally described all soil profiles. A comparison with our own profile descriptions has proven invaluable.

Educational materials are developed such that they can be widely disseminated in electronic and interactive formats, greatly increasing both the scope and the potential for public use. Use of ESRI Story Maps as a framework for Virtual Field Experiences facilitate access to spatially-explicit datasets.

What is the impact on society beyond science and technology?

Amilcare Porporato, the CCZO's Co-Lead PI, answers this question:

"Simple models of social-CZ dynamics have the potential to capture the imagination and interest of the scientific and general public, providing simple and tantalizing explanations for long-term land-management practices. At the Calhoun CZO, we link social-land practices to a remarkable history of soil and land degradation of historical and national importance. Such cross-disciplinary approaches are important to educating citizens about a more respectful use of water and soil and to encourage the next generation to appreciate the usefulness of quantitative tools that address environmental problems."

After visiting the Calhoun CZO for on a two-day visit, Bruno Latour, philosopher of science, suggested he was not fully prepared for what he found at the Calhoun CZO, a landscape so disturbed and eroded by agriculture that nearly a century

after reforestation, the effects of farming were so clearly to be seen and felt.

Changes/Problems

Changes in approach and reason for change

Developing the Calhoun CZO on the USDA Forest Service's Sumter National Forest required a considerable effort on the part of the Lead PI and several PIs and students to interact with USFS managers and NEPA coordinators and to comply with environmental assessment requirements. Our CZO decided early on that we would operate in full compliance with USFS's requirements. Although USFS managers gave us a waiver to begin our project, it took a full year to receive a formal Research Permit for most of our proposed research.

While the USFS has been cooperative and supportive of our research, we were forced to redesign the flux tower in our research plan to comply with USDA Forest Service concerns about safety. We were able to finally get the flux tower approved in 2016 and our flux tower was rapidly erected and has collected near continuous data to the present (2019). The Calhoun PIs consider that we have turned the permitting process to our advantage as we seem to enjoy a large amount of trust on the part of the USFS managers.

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

See above. No new delays.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.