



Critical Zone Observatory National Program

As an introduction to our coverage of the US Critical Zone Observatory National Program, **Dr Tim White**, National Program Coordinator, explains the concepts behind this large-scale research enterprise and how it will help us to better understand the effect of the stresses we place upon the planet

First, could you outline what the Critical Zone is and highlight some of the questions the Critical Zone Observatory (CZO) National Program aims to address?

By its simplest definition, the Critical Zone is the thin veneer of Earth's continental surface that spans from the top of the vegetation canopy through soil to subsurface depths at which fresh groundwater freely circulates. Through the use of 'vegetation canopy' instead of 'trees', and referring to 'freely circulating fresh groundwater' instead of 'groundwater', the definition includes the Polar/Arctic, alpine and desert realms where no trees may exist, and excludes deep connate brines and confined aquifers that clearly are not part of the CZ but are part of the groundwater system. Two examples of scientific enquiry that the CZO Program seeks to address are: 1) the rate at which soils form from various parent materials in differing climatic regimes; 2) the various flow paths of precipitation to the land surface in differing landscape settings, through a watershed and to eventual discharge in a river.

From what context did the CZO National Program emerge? What were the defining reasons for its inception?

The CZO National Program emerged from the convergent efforts of several communities, primarily hydrologic and soil sciences, low-temperature geochemistry and geomorphology, all of which can be categorised as studies of Earth surface processes. Early last decade, the US National Science Foundation (NSF) supported a series of organisational meetings and workshops that drew together these at-the-time disparate groups of scientists. The geochemistry community assumed a leadership role through the inception of the Weathering System Science Consortium (WSSC) that eventually morphed into the Critical Zone Exploration Network. A final planning meeting in Washington, DC in 2005 culminated in a presentation to the NSF by Professor Susan Brantley, Penn State University. Soon after this, a call for proposals was issued by the NSF, which led to funding for the first three CZOs. The next three CZOs were

funded as part of the American Resource and Recovery Act.

How did you become involved in this work and what led to your appointment as CZO National Program Coordinator?

I was involved in organising several workshops leading up to the inception of the CZO National Program and had helped to write a science plan for Critical Zone research, as well as the Frontiers in Critical Zone Science report that emerged from a meeting held at the University of Delaware in 2005. I was also very active in SoilCritZone, a European initiative led by Vala Ragnarsdottir (University of Iceland) and Steve Banwart (Sheffield University), and a successor to that project, Soil Transformations in European Catchments (SoilTrEC), the European counterpart to the US CZO National Program. When the CZO National Program began I was actively engaged in managing science and education activities along a transect of shale study sites associated with the Susquehanna Shale Hills Observatory (SSHO) from Puerto Rico through the Appalachian Mountains to Wales, and was working to establish the bedrock geologic setting of the SSHO. In 2010, the NSF determined that a national coordinator was required – the position was filled briefly by Kevin Dressler, a hydrologist at Penn State, now engaged in research administration at the University. When Kevin resigned the position during summer 2010, I was asked to step in.

How big is the challenge of ultimately integrating all biogeochemical, physical, geological, and other data into systems models that describe function and history? Can a timeframe be placed upon reaching this goal?

This is incredibly complex; an enormous undertaking. I was raised by parents who were active environmentalists and taught me and my siblings about ecology and the complex interconnectedness of life, from the tiniest microbes to the largest predators – how if one member of an ecosystem is removed, the effect will cascade in all directions through the system. These topics are still the subject of high-level ecological research,

especially important to understand now that humanity firmly holds the 'top predator' position on Earth. Critical Zone science takes the next step by considering geology, hydrology and atmospheric science, and how the physical and chemical processes associated with those realms interact with ecosystems and life (biology). The task of assembling scientists from a wide array of disciplines 'in the same room' is huge, let alone getting them to speak the same language and tackle a variety of global-scale interdisciplinary science questions.

The CZO PIs have expressed their goal of catalysing transformative Earth surface science in the coming decade by developing: a unifying theory of CZ evolution; coupled systems models to explore how CZ services respond to anthropogenic, climatic, and tectonic forcing; and datasets that document differing CZ geologic and climatic settings, inform the theoretical framework, constrain conceptual and coupled systems models, and test model-generated hypotheses.

Could you outline your relationship with the European SoilTrEC sites?

Starting with the initiation of the WSSC, the scientific leadership at the forefront of CZ science recognised the need to engage international partners to fully explore the broad range of interdisciplinary questions raised by CZ science. Fortunately, a variety of funding sources were realised including the US NSF, the European Commission, and the Worldwide Universities Network. Each contributed moderate sums of money to support workshops and travel that allowed an international group of scientists to build consensus for a research strategy to address key CZ science questions.

The US CZOs were established first and so US scientists were in a position to share 'lessons learned' with European colleagues; it is fair to state that US contributions were key to helping guide the selection of sites that have since been established in Europe. SoilTrEC has very much led the effort to establish a global agenda, and further leads in considering how to move scientific breakthroughs to the public policy realm.

More specifically, I have worked closely with Steve Banwart (Sheffield University) and others to build cross-site scientific research projects between US and SoilTrEC CZOs, and we have collaborated on graduate student and postdoctoral training using proposal-driven travel grants, travel awards to workshops, and a series of field, lab and modelling workshops in the US and Europe. (For more information on SoilTrEC see: *International Innovation*, 'The state of our soils', October 2011, p81-3).

What are the next steps you must take in order to achieve the broader Program objectives?

The NSF has announced their goal of establishing a network coordinating office with support staff dedicated to education and outreach, data management, and network administration by 2014. We need to establish some sort of formalised governing structure for the network. We certainly need this to coalesce our six CZOs into a true network of sites, people and data. In addition, we need to expand the total number of CZOs to include at least, a Polar/Arctic site, an agriculturally managed site, a coastal site and an urban site. These are all realms that the NSF has identified as of interest to them if funds are available.

Dissemination is an important aspect of your activities. Through what channels are you communicating the broader aims of the CZOs? Are best practices shared amongst each of the Observatories to ensure they are maximising the impact of their work?

I meet with the CZO PIs monthly by teleconference to discuss various issues associated with our collaborative efforts. We hold an annual meeting, in 2012 hosted by the Luquillo CZO in Puerto Rico, to present achievements of the past year, goals for the coming year and strategies for reaching those goals. Last year this event was hosted at Biosphere 2 by the Arizona/New Mexico CZO team and was an 'all hands' meeting that included CZ researchers from outside the CZOs. We have held several special topical meetings attended by US and international researchers on an ad hoc basis. We regularly attend the annual meeting of the American Geophysical Union in San Francisco where we have an information booth, and have also had booth presence at the annual meetings of the Geological Society of America and Soil Science Society of America. We attended an NSF STEM conference in Philadelphia in fall 2011 and participated in the recent US Science and Engineering Festival (USSEF) in Washington, DC. We are considering work on a textbook aimed at upper undergraduate/early graduate students, and of course we must also mention our efforts with *International Innovation*! Each researcher aims to publish their work in appropriate scientific journals and we have organised several special issues for that purpose.

A report prepared by the CZO community at the tail end of 2010, states that 'life on Earth depends on the uninterrupted provision of 'Critical Zone services'. Can you offer your own thoughts of the overall importance of the CZO National Program's work and its likely impacts in light of this statement?

Much work from a variety of scientific disciplines shows that humanity is now the major ecological force on the planet, from consumption of raw materials including food, to moving sediment, soil and rock, to emitting greenhouse gases into the atmosphere that cause our planet to warm more quickly than it might otherwise. To determine if the CZ can sustain the relentless stresses we exert upon it, and whether CZ physical, biological and chemical processes can adapt to the stresses, requires an understanding of those natural processes and how they interact. As a program we must: develop this understanding; communicate this information to society; and transfer this information into the realm of policy development and decision making.

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CRITICAL ZONE OBSERVATORIES
studying the zone where rock meets life

funded by NSF



Rock solid research

An observatory site located on shale bedrock is offering new insights into Critical Zone processes.

Professors Christopher Duffy and Sue Brantley discuss the vital aspects of its successful coordination



Why is Susquehanna/Shale Hills such a significant site for research into Critical Zone infrastructure?

CD: The Susquehanna/Shale Hills Critical Zone Observatory (SSHCO) has a long history of environmental research by Penn State foresters, ecologists, hydrologists and geologists. Important experiments were conducted between the early 1970s and late 1990s on forest water use, modelling of upland catchments, soil moisture dynamics and real-time environmental sensing. This history of research within the site located in the Penn State Forest was an important reason for this site's selection as a National Critical Zone Observatory (CZO). Another significant aspect of the site is the underlying shale bedrock, a geology which is pervasive worldwide but which generally has seen limited research in hydrology, geochemistry, soils and geomorphology.

Could you identify the key challenges faced over the course of your research? How have you overcome this difficulty?

CD: Our greatest obstacle has been logistics for supporting the overlapping and complex experiments being conducted by our research team. These include everything from lightning protection and tree falls damaging instrumentation, to the importance of remote power for maintaining sensors in the field. We have conquered the logistics and science support challenge by digging deep into the Penn State engineering resources, consulting



information technology professionals and through our collaborations with other CZO National Program teams who have experienced similar issues. We are developing an infrastructure guide to observatories as part of our first five-year effort.

What do you believe are the benefits of working with student researchers on these projects, both for the project itself and for the students involved?

SB: Undergraduate and graduate researchers form the core of the science activities at the SSHCO. Each student-faculty team is interdisciplinary, relying on, and soliciting support from, other teams in the conduct of complex experiments. For example, the geochemical weathering team and isotope hydrology team have shared the weekly sampling burden for several years. The ecology team and the soils team have conducted joint experiments on the relation of soil moisture to forest transpiration and sap flow. Each team learns what the other is doing and what their respective scientific results could mean to them. It has been a great way to promote 'team science'.

Can you offer some insight into some of the specific field work you are undertaking?

SB: One of the interesting aspects of the SSHCO is that we have also designed an experiment to look at soil development

as a function of climate. This effort has relied on choosing ridge top sites on Rose Hill shale or a compositional equivalent from New York to Puerto Rico. Our analysis of soil formation along this transect is revealing characteristics of water flow, tree interaction, and rock-water-gas interaction that control how water infiltrates low-permeability rock. Furthermore, the transect work was initiated as a collaboration with other scientists along the transect who work at smaller colleges and universities, some of which are minority-serving institutions. We have incorporated faculty and students from these institutions in our water and soil investigations. The research team and students have now emerged as offering a new way of conducting science that supports disciplinary research while creating the prospect for emerging science at the disciplinary fringes.

How do you serve the international scientific community? Moreover, have you formed any strong relationships with other large-scale research activities to enhance the impact of your work?

CD: Our team has been active in working with the SoilTrEC CZOs in developing the data and implementing the Penn State Integrated Hydrologic Model at each of the EU CZOs. We held our first international modelling workshop in State College in August 2010. We have hosted postdoctoral candidates from each SoilTrEC CZO for a couple of weeks to help develop the required data and integrated models at their site. With funding support from SoilTrEC, we have made field trips to each SoilTrEC site, actively attended and participated in the annual meetings, and served on SoilTrEC committees for data and models. Many of the other CZO participants at Penn State also work with international colleagues to promote CZO efforts abroad.

Influencing understanding of **environmental change**

The **Susquehanna Shale Hills CZO** represents a unique opportunity for researchers to measure and model environmental fluxes and at the same time deliver solutions to critical questions about environmental degradation

LOCATED IN CENTRAL Pennsylvania, the Susquehanna Shale Hills Critical Zone Observatory (SSHCO) is one of the six US National CZOs that are jointly responsible for advancing knowledge on Critical Zone processes. The remit of SSHCO is to study the soil processes and mechanisms that take place above shale bedrock, and the role they play in regulating a number of global fluxes, including carbon and phosphorous. One of the intriguing features of the Shale Hills location is that both climatic and biologic events have been clearly documented here. At least two potentially significant perturbations have occurred in the geologically recent past: a climatic perturbation from periglacial to modern conditions, and a biologic perturbation from anthropogenic clearing of forests during and repeatedly since colonial occupation. These events offer researchers a special opportunity to delve more deeply into how soil production responds to both climate-induced variations and changes resulting from human activities.

THE POWER OF PARTNERSHIPS

The SSHCO enjoys a humid continental climate with sizeable variation in seasonal temperatures, ranging from 33.5 °C to -24.8 °C, and acidic precipitation. This means that study sites in this location can provide valuable insights into soil processes based on a wide variety of environmental factors. To gain such insight, a transect of satellite study sites, all based on Silurian shale bedrock, has been set up as a key

part of the wider CZO infrastructure. These sites run from central New York right down to Alabama, taking in the Appalachian Mountains. At each site the collection of data – such as soil sampling, – gathering of climate data and deployment of gauges, is the responsibility of partner institutions, including Colgate University, Pennsylvania State University, Juniata College, Washington and Lee University, University of Tennessee and Alabama A&M University. Beyond US borders, collection sites that have been set up by collaborative projects in Puerto Rico, managed by Tom Miller, University of Puerto Rico-Mayaguez, and in Wales, managed by Brian Reynolds, Centre for Ecology and Hydrology.

Professor Christopher Duffy, based at Penn State University and SSHCO Principal Investigator from 2008-12, explains that the emphasis of their research is on the quantitative prediction of Critical Zone creation and structure. This is achieved by focusing on the pathways and rates of water and sediments through studying a number of different processes – including geochemical, hydrological, biological and geomorphological – at play within this temperate, forested landscape: “Our interdisciplinary team works collaboratively in one observatory to advance methods for characterising regolith [a layer of loose, heterogeneous material covering solid rock] and its processes,” Duffy elaborates. The group is therefore using both theory and experiments to help predict how the layer of unconsolidated solid material that covers the



MAYA BHATT AUGERS SOIL ABOVE THE SHALE BEDROCK AT SSSHO © MARK SELDERS OF MARK SELDERS PHOTOGRAPHY



GEORGE HOLMES COLLECTING PRECIPITATION WATER SAMPLES FOR ISOTOPIC ANALYSIS © MARK SELDERS OF MARK SELDERS PHOTOGRAPHY

INTELLIGENCE

SUSQUEHANNA SHALE
HILLS CZO

OBJECTIVES

To advance methods for characterising regolith, to provide a theoretical basis for predicting the distribution and properties of regolith, and to theoretically and experimentally study the impacts of regolith on fluid pathways, flow rates and residence times.

PARTNERS

Colgate University • Juniata University • Washington & Lee University • University of Tennessee • Alabama A & M • University of Puerto Rico - Mayaguez • USDA Forest Service-Pacific Northwest Research Station • Princeton University • Temple University • Binghamton University • University of Vermont • USGS • Cornell University • MIT • Harvard • Bucknell University • University of Arizona

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CHRISTOPHER DUFFY focuses his research on developing spatially-distributed, physics-based models for integrated watershed prediction of water, energy, solutes, and sediments. Duffy's early research involved the response of hydrologic systems to stochastic variability, while current theoretical and experimental work involves development of a new method for simulating the 'isotopic age' of water in watersheds and river basins.

SUSAN L BRANTLEY is Distinguished Professor of Geosciences in the College of Earth and Mineral Sciences at Penn State University. Brantley's career as a geochemist has taken her from the deserts of Peru to the glaciers of Iceland. In contrast to many geologists who are strictly interested in rocks and their formations, her work focuses on the chemistry of natural waters both at the surface of the earth and deeper in the crust.



AJ HERRS, UNIVERSITY OF KANSAS, USING A TERRESTRIAL, TRIPOD-MOUNTED LIDAR
© JENNIFER Z WILLIAMS

shale bedrock is distributed and how this layer of substance impacts fluid pathways, flow rates and residence times.

CROSS-SITE COMPARISONS

SSHCZO is contributing important information towards the broader understanding of Critical Zone architecture. Professor Sue Brantley, who works closely with Duffy, describes the relevance of the findings from SSHCZO within this broader National Program, highlighting that over the last five years, since the monitoring infrastructure was first set up at the sites, they have been able to confirm that coupled processes play an integral role in defining how the Critical Zone responds to change: "We are now convinced that integrated, co-located observations and measurements are essential to developing the next generation of predictive models for water, energy and solute cycles at Shale Hills". Such integration has comprised different groups of students – led by a number of highly experienced scientists – taking separate measurements of a number of factors and processes at Shale Hills, including the latent heat flux above the forest canopy, sap flow to estimate transpiration, soil moisture, groundwater, channel flow and comprehensive stable isotope monitoring for ^{18}O and ^2H .

As a result of all these investigations the CZO now has access to a number of different methods to check against the Penn State Integrated Hydrologic Model (PIHM), whilst allowing the working group to further develop their modelling skills. This is driving the team closer towards the ultimate goal of estimating patterns of water, energy, solute and sediment fluxes over space and time. According to Brantley, this experience has been fundamental in enabling them to offer wider support and advice to other CZOs, in particular by engaging in cross-site comparisons: "Our modelling team led by Duffy has been actively helping our colleagues and their graduate students at the Christina River Basin CZO in Delaware, and elsewhere, to implement PIHM at their observatories," she states. They have achieved this in a number of ways, including holding regular teleconferences to help share some of their successes, as well as how they have overcome obstacles.

INFORMING POLICY
IMPROVEMENT AND CREATION

The SSHCZO work is supporting the development of new environmental observation systems needed to help improve awareness and understanding of how fluxes – whether water, sediment, energy or solute – change and adapt over very small spatial distances right up to hundreds of kilometres. By producing coordinated observations that can help to verify these predictions they can also help to inform decision makers attempting to assess future climate uncertainty. To date, they have already had success supporting local agency decision makers through their work creating next generation environmental flux models for the Chesapeake Bay watershed. Other watersheds within Pennsylvania have also been investigated, as the geochemical team build their understanding of shale rock-water interactions: "By improving our ability to measure and model environmental fluxes of water, energy, nutrients and carbon we are fundamentally supporting the next generation of coupled models and co-located observations necessary to solve important questions of environmental change and environmental degradation," observes Duffy.



THE GEOCHEMISTRY TEAM COLLECTS WATER SAMPLES FROM TENSION LYSIMETERS IN THE CATCHMENT © HENRY GONG OF NITTANY MEMORIES PHOTOGRAPHY

Integrating long-term **water studies**

Understanding how water cycles drive Critical Zone processes is essential for planning climate change responses. **Dr Roger Bales** shares his thoughts on an observatory which supports such research

First, could you highlight the context from which the Southern Sierra Critical Zone Observatory (SSCZO) emerged? What are the scientific goals of your work?

A group of researchers had been planning a hydrologic observatory in the Sierra Nevada for several years, having identified it as a priority for integration of hydrologic, biogeochemical and ecological research. Processes at the rain-snow transition elevation, in the mixed-conifer forest, emerged as highest priority. This was partly because it allows for the use of steep temperature gradients with elevation to substitute space for time when studying impacts of a warmer climate.

This group was also active in working with the US National Science Foundation, and other agencies, to create the opportunity for an Observatory Program as a platform for firstly hydrologic and, later, Critical Zone science. The chance to submit a Critical Zone Observatory National Program proposal and collaborate with the US Forest Service research programme at the Kings River Experimental Watersheds, provided the ideal opportunity. Our current

research focus is on water balance, nutrient cycling and weathering across the rain-snow transition, with soil moisture as the integrating variable.

What have been the greatest successes for this project so far?

Our CZO is located at a recently developed research site, but one that fills a critical need in the Sierra Nevada and western US, and that is planned to be active for some time into the future. One success has been based on our ability to attract a creative, dedicated and multi-institutional team of researchers to work together on common science questions. In terms of results, our measures of evapotranspiration along an elevation gradient clearly show very high values in the mixed-conifer forest, as well as highlighting that transitions between water-limited, not-limited and cold-limited forests are more abrupt than previously thought, with a broad elevation band of forests with little water or cold limitation.

What do your summer student internships entail and how do these benefit students in the long term?

The summer student interns get hands-on experience in Critical Zone research by working with SSCZO staff, researchers, graduate students and other student interns. Interns spend most of their time working in the field and living/working alongside US Forest Service staff and people working at the SSCZO, but are also exposed to laboratory work environments. They spend much of the summer in the mountains with limited access to phone and the Internet. Interns work on numerous projects and are exposed to our multidisciplinary research. The positions involve a number of tasks including: assisting with installation of equipment for environmental measurements; construction and maintenance of sampling equipment; making measurements in soils, streams and forests; and data analysis. Most of the work would be field work in the Sierra National Forest at elevations between 1,500 and



2,400 m above sea level. These positions offer entry level and advanced experience for students in their chosen field, while introducing them to other fields of study and employment. Students have the opportunity to network with faculty and students from a broad range of disciplines, which are located at various universities. Past interns have used this opportunity to move into jobs in the private sector, as well as continuing their education in graduate programmes.

Have you undertaken any public outreach activities of note and how important is this to SSCZO's goals overall?

We strive to accomplish our education and outreach goals through K-12 partnerships, undergraduate experiences, publishing results and posting datasets on our website, as well as stakeholder education and media projects. To exemplify the importance of outreach to our overall goals, we have developed an education and outreach mission statement, which is to communicate our research and improve the public understanding of the relationship of the Sierra Nevada snowpack and state water resources in California. Our continuing goal is to foster educational partnerships by continuing to work closely with educational institutions such as Naturebridge at Yosemite to provide instructor trainings on hydrologic concepts and snowpack science. Colleagues will also continue to work with schools and organisations to facilitate hands-on activities for students that focus on how Sierra Nevada hydrology impacts California's water resources. Using our website to improve data accessibility and attract more collaborators to do research at the SSCZO is another an ongoing goal.

A better base for future water processes

The Southern Sierra CZO is breaking new ground supporting investigations into rain-snow transition Critical Zone processes, and at the same time integrating hydrologic, biogeochemical and ecological research

THE SOUTHERN SIERRA Critical Zone Observatory (SSCZO) is located in the Kings River Experimental Watershed, which is a US Forest Service watershed-level research site in the Sierra National Forest. One motivation behind setting up the CZO – one of the six CZOs comprising the US Critical Zone Observatories National Program – is that it provides a unique chance to implement an integrated ecosystem approach to understanding how water cycles and processes linked with water respond to a warming climate. Dr Roger C Bales, Principal Investigator at the SSCZO, explains that their role is to provide a data-rich research platform and infrastructure that will enable scientists to delve into a number of key questions relating to water cycles. These include: what links soil moisture to topography, soil formation and weathering; how vegetation influences water cycles, energy and carbon cycles; and how the variability within landscapes controls how Critical Zone processes respond to snowmelt and rain.

As technologies and forecasting of water cycles improve and expand to admit wider catchment dynamics and Critical Zone processes, the research underway at the SSCZO, and the

knowledge base that the research groups are developing, are increasingly important for helping to guide future decision making around water supply. A project as complex and far-reaching as this is highly multidisciplinary and requires a wide representation of skills. The SSCZO researchers represent some of the best mountain water and climate experts available, with backgrounds in hydrology, geomorphology, soil science, biogeochemistry and ecology. “Our investigators, postdoctoral researchers and students use a combination of continuous ground-based and remotely sensed measurements, field experiments, data analysis and modelling,” points out Bales, “all of which means they need reliable and robust infrastructure and systems.”

BUILDING A SOLID INFRASTRUCTURE BASE

The driving force behind the science models that the SSCZO is setting up is being able to understand the bi-directional linkages that are taking place across the rain-snow transition within the Sierra Nevada region, including how landscape and climate variability are linked with water and material fluxes. These are

multifaceted processes that require some highly technical infrastructure that can support and sustain the research. Part of this infrastructure includes the deployment of a 50-node wireless embedded sensor network, including over 300 sensors, which allow researchers to collect reliable, real-time data about water content from the snow and soil. One of the challenges with such technology is ensuring the sensors are accurate and dependable given the harsh conditions they operate within. It is also imperative that these sensors can survive for long time periods with little maintenance.

As part of this infrastructure the SSCZO group has set up four eddy-covariance flux towers along an elevation transect in the Southern Sierra Nevada. These provide individual measurements on water, energy and carbon exchanges with the atmosphere. By extending out these datasets, researchers can then look at broader critical-zone interactions across different landscape and time scales. The Providence flux tower also provides the main transmission hub for the sensor network. Last year, in collaboration with the University of Arizona, the SSCZO team located two Cosmic-ray Soil Moisture Observing Systems (COSMOS) in the same place as two of the flux towers; the P301 and the Shorthair towers. This system is measuring soil content over sizeable distances by recording low-energy cosmic-ray neutrons. Data from the COSMOS is then made available in real-time to researchers through a specially developed data portal.

The National Ecological Observatory Network (NEON) is also an important part of the SSCZO infrastructure. Bales describes how its presence in California is planned as a transect extending from the oak-grassland ecosystem at the San Joaquin Experimental Range, through the mixed-conifer forest. The SSCZO has already set up its four flux towers along this transect, and NEON intends to set up three flux towers in the same place: “The NEON measurement suite will go well beyond what we have been able to do,” observes Bales, “meaning it will provide exciting new opportunities for process-level research”.

FIELD HYDROLOGIST MATT MEADOWS CHECKING DATA AT THE BASE OF AN EDDY-CORRELATION FLUX TOWER



INTELLIGENCE

SOUTHERN SIERRA
CRITICAL ZONE
OBSERVATORY

OBJECTIVES

A community resource, providing both a platform for research by investigators from multiple disciplines and a vigorous research programme aimed at yielding general knowledge and tools for understanding the interactions between water, atmosphere, ecosystems and landforms in the Critical Zone.

PARTNERS

UC Davis

UC Berkeley

UC Irvine

UC Santa Barbara

University of Wyoming

University of Nevada, Reno

Pacific Southwest Research Station,
USDA Forest Service

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ROGER BALES is a Founding Professor of Engineering at the University of California, Merced, and is Director of the university's Sierra Nevada Research Institute. His research group and collaborators maintain an active programme of field-based and modelling research in mountain hydrology, climate and biogeochemistry.

The SSCZO researchers represent some of the best mountain water and climate experts available, with backgrounds in hydrology, geomorphology, soil science, biogeochemistry and ecology

DELIVERING HIGH QUALITY DATA

The investigations currently underway within the SSCZO include surface-groundwater interactions, single-tree experiments, weathering and geophysical studies, biogeochemical investigations and spatial data gathering using remote-sensing tools. These experiments and investigations are providing a vast amount of information that can, at times, be challenging to manage. Bales explains that they have employed a number of strategies to better facilitate data management and integration: "Our priority has been to archive and serve both raw data and datasets that have undergone rigorous quality assurance and quality control for use by both the SSCZO team and the broader community". With hundreds of continuous sensors spread across the observatory site, taking data through such intensive quality control and assurance steps can be a challenge and requires the participation of the whole SSCZO team.

INFORMING CLIMATE
CHANGE ADAPTATION MEASURES

This observatory has been particularly successful, with demand for their observatory to serve as a community platform for research.

The researchers are planning to progress their activities by extending the studies of water and biogeochemical cycles below the soil horizons, down into bedrock. This work requires drilling shallow wells that will provide a place to locate instruments as well as allow samples of bedrock to be taken. Bales anticipates that further investment in research infrastructure in and around the SSCZO will come from the US National Science Foundation's NEON Program which will provide an important opportunity to extend their measurements and enhance the links to biodiversity and biogeochemical cycles.

All of this work feeds into the broader global-change research landscape by providing scientific knowledge on how the mountain landscape and ecosystems are likely to respond to changes in temperature and to the water cycle. As Bales outlines, adapting to climate change means that we must also adapt to changes that are taking place within the water cycle – precisely the information the SSCZO are collecting and analysing: "We are providing accurate measures on the water cycle and using that work as the foundation for accurate predictions for future changes, all of which will support the wider climate change research".

CZO INVESTIGATORS, STUDENTS AND VISITORS AFTER A SPRING SNOW OUTING



Shedding light on watershed erosion regimes

Dr Suzanne Anderson

highlights why Boulder Creek is the perfect location to discover more about the legacy of weathering and erosion, and how this can inform how watersheds will respond to climate change



Why is Boulder Creek Critical Zone Observatory (CZO) such a significant site for research into Critical Zone structure?

The Boulder Creek watershed stretches from the top of the Colorado Front Range onto the western Great Plains. Within this watershed we can identify areas that have experienced different erosional events that should be expressed in differences in Critical Zone architecture. In our view, Boulder Creek presents a set of natural experiments to explore interactions of erosion and weathering – glaciers scoured and plucked valleys in the headwaters, while the master rivers cut canyons that extend from the Continental Divide in the Front Range to the Plains. The entire watershed was affected by Quaternary climate change. We are particularly concerned with learning more about how the depth of weathered rock, the thickness of soil, and character of these surficial layers are controlled by this history. Because subsurface structure takes time to develop and evolve, this question leads us to consider how weathering and erosion processes and their rates have changed over past climate cycles. This perspective informs

understanding of how the system will respond to future perturbations. As part of this, we explore the operation of modern processes within the watershed. Water is the focus of these questions, and the Colorado Front Range offers strong gradients in precipitation amount and precipitation type (rain or snow) within which to frame these questions.

What obstacles have you faced coordinating research across such a vast area?

With respect to managing research in a 1,160 km² watershed with 2.6 km of relief, we have focused monitoring in a few key locations that exemplify the different erosional regimes in the watershed. The greatest challenges, however are in bringing about collaboration between diverse researchers. Building this community is an ongoing process. A graduate-level course on the Critical Zone knitted students together and introduced them to different disciplines, tools and perspectives. Faculty, students and staff meet regularly to discuss logistics, findings, new ideas and planning.

The project takes a highly multidisciplinary approach. How do you draw on these different disciplines to generate knowledge on the area?

Our team spans geomorphology, hydrology including ecohydrology and snow hydrology, geophysics, biogeochemistry and microbial ecology. Each researcher is involved in an aspect of the overarching questions we have posed, including how Critical Zone architecture evolves from erosion and weathering processes integrated over time and how the Critical Zone functions (water flow, erosion processes, biogeochemical processes, solute generation and flux). There is wonderful cross-talk between the research efforts on these main themes. For instance, we could see differences in vegetation on different aspect slopes and

had a sense from digging soil pits to sample soils and their microbial communities that rock weathering also differed with slope aspect. But when shallow seismic refraction surveys showed that the depth to fresh rock was much greater on north-facing slopes than on south-facing slopes, we knew that we were working on something really significant. We welcome researchers from elsewhere coming to work in our sites, bringing their own tools, questions and perspectives. Our data is available on our website, and can be discovered via a Google Earth interface. We cannot do it all, and so are happy to have others take advantage of the sites.

How do you serve the international scientific community and have you formed any strong relationships with other large-scale research activities to enhance the impact of your work?

Our initial science team included two German researchers who brought shallow geophysics to the project. We hosted an International Student Critical Zone Symposium with the European Commission funded SoilTrEC project in 2011. This brought together 25 students and postdoctorates to tour the Boulder Creek CZO and to share their research findings in a workshop held in conjunction with the 9th International Symposium on the Geochemistry of the Earth's Surface. This summer two of our graduate students will join others to attend a SoilTrEC workshop in Crete on reactive transport. I am working with researchers at the University of Strasbourg in France using U-series disequilibrium to quantify weathering rates. Other possible international collaborations are still waiting on a confirmation of funding. In each case, these collaborations bring a range of important analytical tools or perspectives to our field site opportunities.

Using sound waves to gain deep-time perspectives

Geophysical tools have allowed Boulder Creek CZO researchers to probe weathered rock, supporting the documentation of Critical Zone architecture in different erosion regimes, holding significance for the surrounding area

AFTER FIVE YEARS gathering data, the Boulder Creek Critical Zone Observatory (CZO) – one of six that comprise the CZO National Program – is now generating unique insights into watershed processes. Based at the University of Colorado at Boulder, this CZO was set up to build a more robust understanding of how erosion and weathering control the evolution of Critical Zone architecture. Principal Investigator Dr Suzanne Anderson explains that through the accumulated observations from a wide range of methods, including geophysics, cosmogenic radionuclide dating, tracer experiments, hydrologic and meteorological monitoring, and microbial surveys, they can now start to “connect the pieces and see links between different components”. The observations guide and constrain quantitative models of Critical Zone evolution and function, which provide a sound basis for predicting response to climate or land use change.

Boulder Creek in the Front Range of Colorado was identified as an appropriate location due to its proximity to the University of Colorado, the existence of legacy data in the alpine headwaters from the Niwot Long Term Ecological Research (LTER) site and other studies, and most

importantly, because of the varied erosional histories in different parts of the watershed. From glacial valleys, to bedrock canyons, to alluvial terraces, the 1160 km² watershed offers several concurrent natural erosion experiments. At selected sites in different erosion regimes, the Boulder Creek CZO team hopes to record the makeup of the Critical Zone, constrain ages of surfaces, and monitor processes in watersheds. They have been developing new measurement infrastructure to aid their ability to monitor processes, and have been creating models that address a wide range of Critical Zone evolution questions. In doing this work they are developing a community of multidisciplinary scientists as well as fostering public outreach.

SEISMIC SURVEYS

Measuring soil thickness and the depth to fresh rock are notoriously challenging but essential to help understand the Critical Zone. Shallow seismic refraction surveys have provided the Boulder CZO group with invaluable data to observe weathered rock under the ground. Sound waves produced from a hammer striking the ground surface are used to reveal the subsurface. The method relies on variations in the speed at which the seismic waves move through the subsurface to infer its structure and composition: “In transects that criss-cross our sites, we can document the speed structure of the subsurface, which can be translated into the degree of weathering. We are then armed with observations that our conceptual and numerical models of hillslope evolution must incorporate,” Anderson states. When combined with knowledge of surface lowering rates determined with cosmogenic radionuclides, the seismic survey data reveals the deep history represented by the Critical Zone. “Rock and sediment delivered to streams today has spent many tens to hundreds of thousands of years being exhumed and residing in soils on

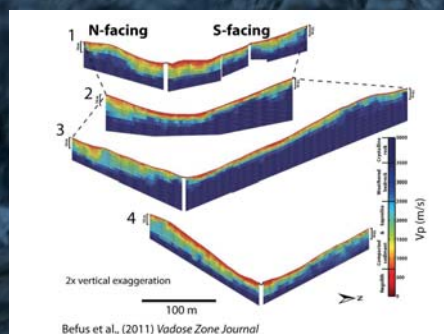


FIGURE 1: SEISMIC REFRACTION REVEALS ASPECT DIFFERENCES IN DEPTH TO FRESH ROCK (DARK BLUE)

INTELLIGENCE

BOULDER CREEK
CRITICAL ZONE
OBSERVATORY

OBJECTIVES

To develop a robust predictive ability for how the structure and function of the Critical Zone evolves and how it will respond to projected climate and land-use changes. Boulder Creek CZO uses natural erosional and climatic experiments posed by the landscape of the Colorado Front Range to develop understanding of the linkages between weathering, erosion, ecosystems and climate.

PARTNERS

U.S. Geological Survey

Keck Geology Consortium

Niwot Long Term Ecological Research (LTER)

FUNDING

National Science Foundation (NSF) – grant no. 0724960

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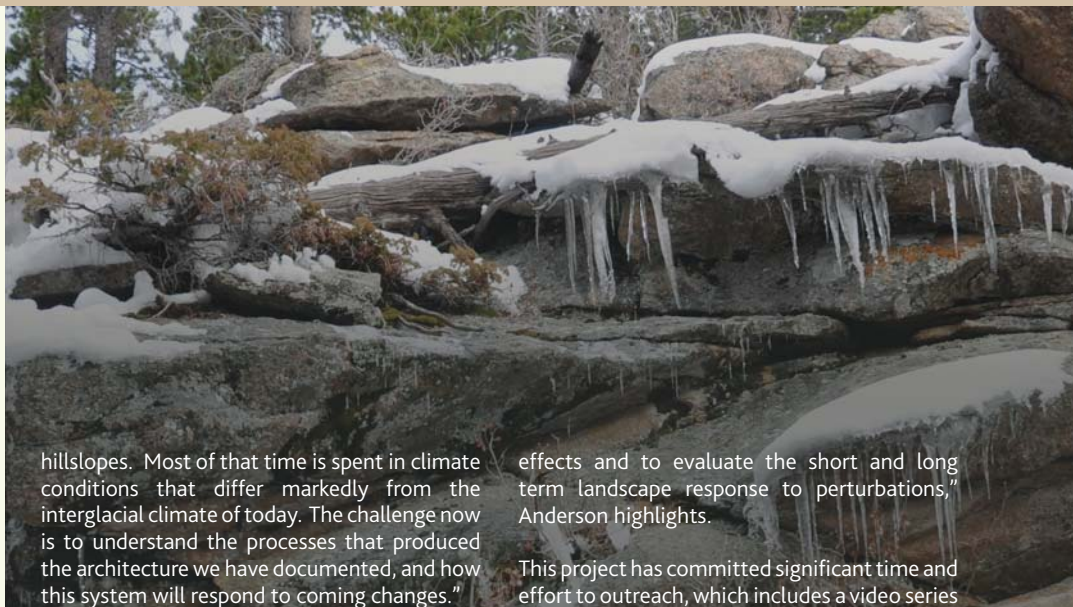
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hillslopes. Most of that time is spent in climate conditions that differ markedly from the interglacial climate of today. The challenge now is to understand the processes that produced the architecture we have documented, and how this system will respond to coming changes."

COMMUNICATION AND COLLABORATION

Partnerships with other institutes and agencies are an important component of the research taking place through the Boulder Creek CZO. One such activity involves collaboration between the observatory and the US Geological Survey (USGS) to evaluate the effects of wildfire on stream water quality. Wildfires are major events in this region of the US and dramatically impact ecosystems and a wide range of natural processes, including hydrology, sediment transport and surface energy balances. In September 2010 a wildfire in Fourmile Canyon burned around 2,600 ha of the Boulder Creek watershed. Existing Boulder Creek CZO monitoring sites provide perspective and context from undisturbed watersheds for data gathered in new sites established in the burned area. By focusing on stream water quality and flow regime, Anderson states, "the team will address the direct impacts of wildfire on aquatic life and will document the recovery of the watershed from the fire, questions that are of interest to people who live in the burned area, as well as areas downstream like the city of Boulder". This type of natural occurrence also provides the chance to examine how dramatic events like wildfire impact the longer-term evolution of the watershed: "As the Fourmile Fire area is so close to our CZO sites, study of its aftermath presents a perfect opportunity to develop the instrumentation required to capture the

effects and to evaluate the short and long term landscape response to perturbations," Anderson highlights.

This project has committed significant time and effort to outreach, which includes a video series and Google Earth fly-through the landscape on the Boulder Creek CZO website, and contributions to a national CZO cyberseminar series. Anderson firmly believes scientific communication to be an integral component of the research that is taking place at the CZO: "Outreach is a vital part of our work, as it helps cultivate the next generation of scientists and enriches the lives of all involved," she outlines. The belief of the group is that contributing to public understanding about how the land and their surroundings have been shaped by natural processes over eons gives people a new appreciation of this natural environment. To date, they have had fantastic feedback on workshops run for school children, where they explore landscape evolution on a stream table, the structure and water content of snow, the influence of fire on runoff, and runoff generation in a large watershed.

THE BIGGER PICTURE

Many of the research activities taking place at the Boulder Creek CZO are fundamental in nature, but hold implications for the surrounding area, such as water quality. Whilst the observatory is not specifically making environmental policy recommendations, at a broader scale this work is certainly delivering important information for the development of policy. Anderson offers an example of Diane McKnight's investigations into the quantity and character of dissolved organic matter in stream water and how it is controlled by watershed processes: "This research is very relevant to water supply as high concentrations of organic matter can lead to formation of deleterious disinfection by-products in drinking water," she observes. Work on marginal snowpack dynamics, soil moisture and ecohydrology helps understand annual forest fire risk – an important question in western North America. Whilst all of this work is clearly focused on addressing many of the unanswered environmental science questions, the answers they produce and any potential solutions offered are of much value to policy makers.



Reaching a watershed in understanding environmental processes

Through their work with critical zone processes in watersheds, **Professor Frederick Scatena** and colleagues are developing methodologies that are now being applied elsewhere. Here, he outlines why these efforts have been so successful



Can you outline the key objectives of the Luquillo Critical Zone Observatory (LCZO), and its importance to the wider CZO network?

The key objectives for the LCZO are to quantify how Critical Zone processes, water balances and mass fluxes differ in landscapes with contrasting lithology but similar climatic and environmental histories. Although bedrock lithology and chemistry have been considered primary state factors in landscape and soil development for over a century, the influences of lithology on denudation (the wearing away of the Earth's surface), hydrologic routing and geochemical processing is poorly constrained in most studies. To address this challenge the LCZO uses the natural laboratory of the Luquillo Mountains to quantify and contrast how Critical Zone processes in watersheds underlain by quartzdiorite and volcanoclastic bedrock are coupled and decoupled with climatic conditions and hydrologic, geochemical and biogeochemical cycles. In doing so we provide the national CZO network with a study site in a humid tropical environment where some of Earth's highest

rates of erosion occur. Because of the urban and agricultural land use surrounding the Luquillo Mountains, the LCZO also provides the national CZO network with a range of land uses and novel Critical Zones that can be studied.

What have been the key findings of the various research projects at the LCZO?

Key findings can be divided into groups: those that are essential to understanding the local Critical Zones and Critical Zones on tropical mountains; and those results that have widespread application. For example, one group that is looking at the landscape scale spatial distribution of soil carbon has developed ways to predict how much soil carbon there is at any location in the forest with up to 70 per cent accuracy. This is critical because approximately half of the terrestrial carbon is stored in soils, but our ability to predict where and how much is stored below the surface has been extremely limited. Locally these results are useful for natural resource managers involved in regulating carbon resources. At the same time, the sampling and statistical techniques they have developed to make these predictions have widespread applicability. Likewise, our earlier work on environmental stream flows and water extraction systems has not only been used to develop local municipal water systems that are appropriate and sustainable, but the methods and approaches we have progressed are now being applied and adapted at other research locations.

How is the LCZO involved in outreach and education programmes?

Our goal is to engage students from Puerto Rico and around the world. The University of Puerto Rico is one of our many collaborators and their undergraduates and graduate students are involved both in the research and use of data and the contribution of data to our websites. In addition, we have had a

longstanding tradition of engaging students from other countries in Latin America and Europe. In the past few years students from The Netherlands, France, Mexico, Costa Rica, Panama, Colombia and other Caribbean Islands have been actively engaged with the site.

How are you collaborating with other research institutions both in the area and in other countries in order to inform and communicate your results?

Peer-reviewed and web-based publication of environmental data are the primary ways we disseminate information. In addition we host annual research meetings, organise topic-specific workshops with local natural resource managers and present results at international conferences and during web-based seminars. Our data collection and sampling processing is also coordinated with other research groups working in the area. For example, our rainwater chemistry is collected and analysed in coordination with the US National Acid Rain Deposition programme; our stream flow measurements are done in collaboration with the U.S. Geological Survey and our forest measurements with the US Forest Service. We also exchange soil, plant and water samples with various laboratories to ensure compatibility in our measurements.

What are the benefits of the cross-disciplinary nature of research at the LCZO?

As we are able to monitor and quantify the Earth's systems, it is apparent that there are many complex relationships between humans and their geologic, climatic and biologic environments. Furthermore, these relationships change over time and space. Understanding these dynamic relationships requires an integration of disciplines and coordinated data collection. Thus coordinated cross-disciplinary research is not just beneficial, it is essential to understanding and managing the landscape.

Knowledge based on bedrock

With an expansive natural forest mountain setting as its research laboratory, the **Luquillo Critical Zone Observatory** has been helping inform both a wider understanding of environmental processes and policy making

LOCATED IN THE Luquillo Mountains in north-eastern Puerto Rico, the Luquillo Critical Zone Observatory (LCZO) has been specifically designed to address questions regarding how Critical Zone processes differ throughout diverse bedrock landscapes that have similar climates and land use. The infrastructure and tools that have been set up at this observatory are located on three rock types – quartz diorites, volcaniclastics and their associated contact metamorphic rocks. These bedrocks are some of the fastest eroding watersheds in the world, and it is hoped that by improving our understanding of the differences in Critical Zone processes between these bedrocks, decisions on the long-term use of water and soil resources can be better informed and the sustainability of this use can be ensured.

RESEARCH DRIVEN BY COLLABORATION

Frederick N Scatena, the scientist in charge of the LZCO – which is part of the wider Critical Zone Observatories National Program – explains that their work involves investigating the flow and transformations of material within the Critical Zone: “Our research has demonstrated that Critical Zone processes do, in fact, vary on different bedrocks and in different landscapes’ positions. These processes produce soils that vary in their structure, water holding capacity, how they store carbon, water and nutrients and how water and material flow across the landscape”. These are important findings because they highlight that for some nutrients and elements, abiotic factors, such as bedrock chemistry and landscape position, are major predictors of their abundance and distribution. In addition, they indicate that for other factors, such as carbon and nitrogen levels, the dominant control on their spatial distribution is biological processes. “Understanding the differences in processes,” states Scatena, “allows us to identify hot spots on the landscapes that are susceptible, or in some cases resistant, to environmental change.”

The LCZO is a shining example of how partnerships and alliances from a number of universities and agencies can result in successful science outcomes. Principal researchers, staff and students from the University of Pennsylvania, the Pennsylvania State University, the University of

It is hoped that by improving our understanding of the differences in Critical Zone processes between these bedrocks, decisions on the long-term use of water and soil resources can be better informed



California at Berkeley, the University of New Hampshire, the University of Puerto Rico, the U.S. Geological Survey and the US Forest Service International Institute of Tropical Forestry are all collaborating to foster a positive research environment within the Luquillo Mountains. The LCZO also offers opportunities for collaboration with a number of other US and international universities and research centres. It is these relationships that hold the key to much of the success that they have enjoyed.

FACTORING THE DIFFERENCES IN PROCESSES

The group's research attempts to shed light on a number of existing uncertainties regarding environmental processes, particularly the overarching question of how and when landscapes with different Critical Zone structures respond to environmental change. To address this they make detailed, high frequency measurements of climate, all components of the hydrologic cycle and a number of biogeochemical processes. The differences in these processes can have significant implications on the long-term sustainability of water and soil resources, as Scatena outlines: "Understanding how abiotic and biotic processes interact across the landscape provides us with the ability to predict how the region and its components will respond to climatic and environmental change and the sustainability of current land use practices".

Watershed analysis is an important part of the LCZO's work because the location experiences some of the most rapidly eroding watersheds in the world. It is an incredibly dynamic landscape with on average three rainstorms per day. This means that the researchers have a unique opportunity to measure a wide range of hydrologic and biochemical processes at much more regular periods that are not available in other locations: "This means we can gain a fundamental understanding of the mechanisms involved in changing watersheds," notes Scatena. However, working in such inhospitable forest conditions can present major obstacles for setting up the monitoring equipment and the ongoing research activities: "The logistics of working in a rainy and steep environment is a continual challenge," explains Scatena. "This year landslides damaged the roads to two of our central research sites. The high humidity also creates challenges for our field electronics."

MANAGING COMPLEX DATA

To support such a diversity of research projects investigating a wide range of factors and processes, including deep weathering, riparian zone dynamics, soil carbon accumulation and fluvial geomorphology, the LCZO provides a suite of highly technical infrastructure. Some of the field equipment that is available to the research teams includes stream flow gauges, instrumented soil pits and weather stations. The data that results from the research activities is extensive and complex and requires a dedicated information management system to help both preserve and distribute the data

so it can be used for predictive modelling and comparisons across different sites. This system is based on the philosophy that the best form of data management involves data that has been amalgamated in peer-reviewed journals and that which is also made easily accessible through online portals.

In recognition of the importance and scale of this component of the observatory, they have employed a full time data manager and set up a central data system which incorporates a quality controlsystem. This system is integral to compiling, combining and archiving all the information that comes directly from the LZCO investigations and is linked to the CZO National Portal. Maintaining the infrastructure is also critical to ensuring the sustainability and validity of the data. The LCZO group has a number of upgrades in the pipeline for existing infrastructure and measurement tools as well as new installations proposed, such as the multiple quantitative soil pits planned both for the intensive research sites and throughout the Luquillo Mountains.

BUILDING ON OLD DATA TO CREATE NEW INFORMATION

At present, the collaboration is focused on delivering a preeminent data management system and ensuring the infrastructure is of the highest standard: "In the future, as understanding of the relatively undisturbed forested Critical Zones improves, we will work to understand the human-developed Critical Zones of agricultural and urban environments," observes Scatena. One of the important outcomes of all of the different research projects underway at LZCO is that they combine to form a wider understanding of environmental processes, which in turn will be integral to informing the development of future policy. In Scatena's opinion, understanding the differences between natural and human altered Critical Zones brings with it an ability to predict the response of the landscape to local, regional, and globally induced changes: "This already has and will continue to help determine where to focus our land use management activities and where on the landscape sustainable and unsustainable practices will occur," he states. Ultimately, whilst the group is building on decades of excellent research on the Luquillo forests, linking and synthesising this information with new information from the geological and hydrological sciences to develop policy guidelines takes time and a continued, ongoing commitment – something they have already demonstrated in abundance.



SOIL SAMPLING

INTELLIGENCE

LUQUILLO CRITICAL ZONE OBSERVATORY

OBJECTIVES

To quantify and compare Critical Zone processes in landforms and watersheds underlain by three different rock types, granodiorites, volcanics, and their associated contact metamorphic rocks. Individual research projects include studies of deep weathering, soil formation and soil carbon accumulation, riparian zone dynamics, fluvial geomorphology, and meteorology.

PARTNERS

The USGS Water-Energy-Biogeochemical Budgets Program (water.usgs.gov/webb)

The USDA-Forest Service International Institute of Tropical Forestry (www.fs.fed.us/global/iitf)

El Yunque National Forest (www.fs.usda.gov/elyunque)

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Bringing Earth sciences to life

Dr Jon Chorover shares his insight into an interdisciplinary observatory which supports Earth scientists in testing their hypotheses on climatic and water cycle variation in the Jemez River Basin and Santa Catalina Mountains



What are the key research objectives of the Jemez River Basin and Santa Catalina Mountains Critical Zone Observatory (CZO)?

Our overarching goal is to develop the theory of Critical Zone evolution, which requires making solid foundational linkages between event-based process dynamics – such as hydrologic and hydrochemical responses occurring today in catchments – and long-term geomorphic change of the landscape. Toward that goal, the research objectives of our CZO are first to develop a cross-disciplinary natural laboratory for observation and modelling of Earth surface science of semi-arid environments, and secondly to measure the effects of climate, lithology and disturbance variation on Critical Zone structure, function and evolution in the water-limited southwestern US.

Many of the CZOs work as interdisciplinary collaborative projects. How does the Jemez River Basin and Santa Catalina Mountains

CZO collaborate with a range of researchers and institutions in order to produce a broad range of results?

Our CZO includes two sites, the Jemez River Basin located in the Jemez Mountains of northern New Mexico and the Santa Catalina Mountains located in southern Arizona. This distributed CZO design allows us to extend the gradient in climate across a broad range of temperature and rainfall, while also working at sites that are accessible to researchers and collaborators across a wide swath of the southwest. While the Santa Catalina Mountains site is readily accessible to University of Arizona researchers since it represents the northern mountain block boundary of the Tucson Basin, the Jemez River Basin is readily accessible to our collaborators at the University of New Mexico and Los Alamos National Laboratory, since it is situated north of Albuquerque. In addition, we work closely with the federal agencies who manage the landscapes at both locations, including the Department of Interior which manages the Valles Caldera National Preserve and is our focus of study in the Jemez River Basin, and the Department of Agriculture (National Forest Service) who manages the Coronado National Forest which contains the Santa Catalina Mountain sites.

To what extent do students form an important part of the research team and how are you involved with outreach programmes?

Our CZO supports, or has supported, 14 PhD or Master of Science students, 12 undergraduate students and four postdoctoral scholars. These 'students' form the core of our team, as they are the members most actively involved in collecting data, running simulations and ultimately teaching us all, in real-time, what they are learning. Since most of our CZO

personnel are located at the University of Arizona, our entire group of faculty, staff, postdoctoral scientists and graduates students meet weekly for two hours to discuss emerging research questions, receive research updates from students and develop questions or plans for future research. These meetings are the lifeblood of our progress, because this is where we are learning to speak the language of multiple collaborating disciplines and finding places where we can effectively help each other with complementary tools and ways of looking at the Critical Zone system. Many of our students and faculty are actively involved in outreach through bringing Critical Zone science into local K-12 schools, and also through active engagement in the University of Arizona's Biosphere 2 programme, which reaches thousands of visitors annually and now has a large exhibit on Critical Zone science.

How have the findings in this particular CZO had an effect on the wider knowledge of Critical Zone infrastructure?

Each of the CZOs was funded to test a specific set of hypotheses conceived independently. Therefore, the type of infrastructure (such as instrumentation) being developed at each site is optimised for answering site-specific questions. However, the principal investigators associated with each of the sites began meeting as a large group soon after funding was initiated, in order to start developing a common denominator set of measurements and associated infrastructure, in order to best enable cross-CZO research. As a result, the development of a wider knowledge of CZO infrastructure is really the product of our collective CZO National Program and the pro-active encouragement by the National Science Foundation – a key funder of the CZO National Program – to develop a common set of metrics.

Predicting soil and catchment evolution

Since its inception, the **Jemez River Basin and Santa Catalina Mountains CZO** has been offering researchers a unique opportunity to examine how variability in energy and water fluxes impact Critical Zone processes

OUR UNDERSTANDING OF how the Critical Zone functions in response to energy inputs is still generally poor. In order to answer many of the questions about how the feedbacks between energy and mass fluxes are impacted by physical and chemical gradients, the Jemez River Basin and Santa Catalina Mountains Critical Zone Observatory (CZO) provides two locations where scientists can test their ideas and theories. As a key part of the CZO National Program, this observatory is specifically focusing on how variability in energy input influences Critical Zone structure and function. There are two sites that comprise this CZO; the Jemez River Basin of northern New Mexico, which is on rhyolitic bedrock, and the Santa Catalina Mountains in southern Arizona, which is located on granite and schist.

Principal Investigator Dr Jon Chorover who, along with Dr Peter Troch, leads the Jemez River Basin and Santa Catalina Mountains CZO activities, explains that their group is focusing on water and reduced carbon because these constituents represent climatic and biological drivers of geochemical weathering and physical erosion: "Our CZO proposes that Critical Zone structure and function can be predicted from a precise and quantitative understanding of energy input to the Critical Zone in the form of fresh water and fixed carbon, which we term 'effective energy and mass transfer' (EEMT)". He notes that in the semi-arid southwestern US where their two sites are located, these two are often correlated. Chorover highlights that a result of limited water availability at these sites, the plants that are present also limit their photosynthetic activity, which controls ecosystem net primary production: "We are finding that EEMT is indeed predictive of key and diverse processes of Critical Zone evolution, including solute and sediment effluxes from soils and catchments and valley density formation".

DEVELOPING A DIVERSE FLUX TOOLBOX

The Jemez River Basin and Santa Catalina Mountains CZO has been specifically structured around four cross-cutting research themes; ecohydrology and hydrologic partitioning; subsurface biogeochemistry; surface water dynamics; and landscape evolution. These four themes have driven the development of the combination of field and laboratory-based measurements which include conceptual, analytical and numerical modelling approaches. The measurement tool box they have put together is an extensive one. In addition to the continuously sensed conditions and fluxes, they have developed a range of sampling devices installed throughout the CZO to collect atmospheric-derived

particulate matter, pore waters and surface waters, but a good deal of sampling is also carried out in person, as Chorover outlines: "Not all of our field measurements rely on these sampling devices, and a significant amount of field datasets are collected in campaign-style outings, such as extensive snow or soil surveys, where we collect field data in addition to biological specimens, soils, sediments, rock, etc., for detailed analysis upon returning to the laboratory".

The team collaborations have led, for example, to the development of a numerical geomorphic model that describes the co-evolution of topography, hydrology, soil development and vegetation in the southwestern US. Another major success is their continuing refinement of the EEMT model of Critical Zone structure and function which is now capable of including components such as the point-scale impacts of ecosystem production of reduced carbon and the lateral influx of water from upslope: "Careful development of our CZO infrastructure is resulting in significant breakthroughs; through all of this work we are coming closer than ever before to not only closing the water, carbon, sediment and solute fluxes at the catchment scale, but also to better understanding the fascinating mechanisms of their interaction," Chorover explains.

TURNING OBSTACLES INTO OPPORTUNITIES

One of the major challenges this CZO has had to overcome in its short existence was the 2011 Las Conchas wildfire, which, at the time, was the largest wildfire in New Mexico state history. The fire burned through a significant amount of the Jemez River Basin site – around 630 km² of vegetation. It is the researchers' opinion that although this fire was a tragedy, these natural events do offer opportunities to complete investigations that would otherwise be impossible. "While such a disturbance poses a major challenge for watershed-scale research, it has also introduced unique opportunities for



Following the Los Conchas wildfire in 2011, the Jemez-Santa Catalina CZO team moved quickly to install instrumentation in sites that were subjected to differing intensities of fire in order to better understand the impacts of such disturbance effects on Critical Zone processes.

Careful development of the CZO infrastructure is resulting in significant breakthroughs

INTELLIGENCE

JEMEZ RIVER BASIN AND SANTA CATALINA MOUNTAINS CRITICAL ZONE OBSERVATORY

OBJECTIVES

The observatory is designed as a natural laboratory for the Earth science community to test hypotheses related to Critical Zone function in relation to climatic and water cycle variation. The working group will examine the impacts of space-time variability in energy and water flux on coupled Critical Zone processes along two well-constrained climate gradients.

PARTNERS

University of Arizona

Arizona State University

University of New Mexico

Los Alamos National Laboratory

Valles Caldera National Preserve

Coronado National Forest

Idaho State University

FUNDING

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JON CHOROVER received his PhD from the University of California, Berkeley in 1993. He is Professor of Environmental Chemistry and heads the Environmental Biogeochemistry group in the Department of Soil, Water and Environmental Science. His research group focuses on biogeochemical processes occurring in soil, sediment and water. Of particular interest are components and processes that influence the form and mobility of metals and organics in the Critical Zone.

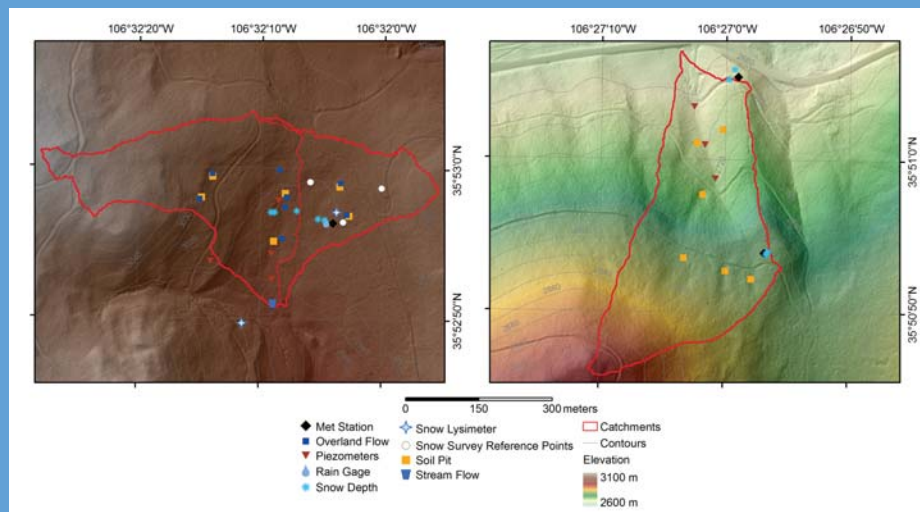


FIGURE 1. The Jemez-Santa Catalina CZO employs a nested catchment design for instrumentation, with a focus on intensive instrumentation of zero order basins (ZOBs). Shown in this image are two instrumented ZOBs in the Jemez River Basin site. Left side shows instrument array in the unburned mixed conifer ZOB in La Jara Catchment and right side shows the corresponding array for the burned mixed conifer ZOB on Rabbit Mountain. Both sites are within the Valles Caldera National Preserve, NM.

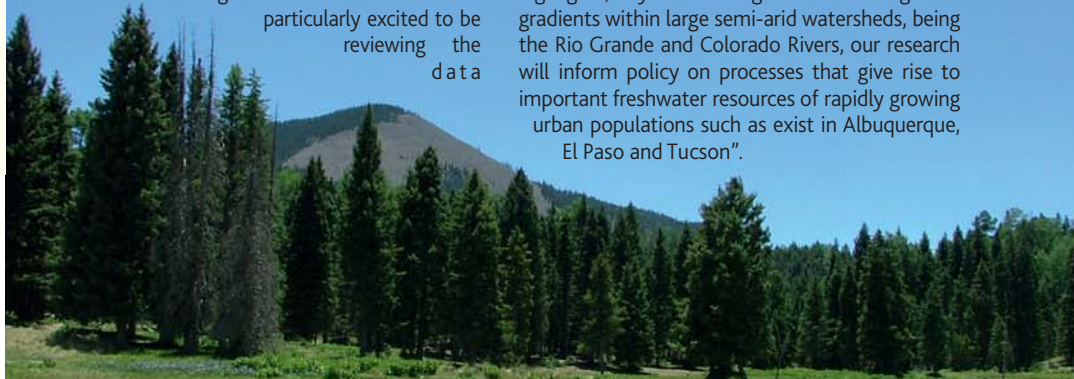
interdisciplinary Critical Zone studies of this disturbance effect that is so profoundly important to western forested landscapes,” Chorover points out. They quickly made the decision to allocate some of their resources to mobilise collaborative studies of burn effects, including instrumentation of a mixed conifer catchment that was severely burned, in order to monitor impacts and recovery, in comparison to an unburned, similarly instrumented catchment (see Figure 1). It transpires that this was a wise decision given wildfire is one of the most critical natural disturbance events to affect significant step changes in Critical Zone structure and function within the forested montane landscapes that are found throughout the southwestern US, and which dominate the Jemez River Basin CZO environment. “By re-focusing our research trajectory, we were able to turn this massive ecosystem disturbance into a unique opportunity for Critical Zone research,” observes Chorover.

After spending the majority of the first couple of years of operation confirming the best locations for installing the instrumentation arrays and ensuring that the instruments are on the ground and operational, the group is now looking forward to being able to capture and analyse some real data. Currently well into the data acquisition period of the project, they are examining datasets that have been gathered on soil materials from pit excavations, and aqueous solutions collected during their passage through the porous weathering geomedia. The researchers are particularly excited to be reviewing the data

from periods of snowmelt and summer monsoon events of 2010 and 2011 because they are vastly different from each other; 2010 was a relatively wet year, whereas 2011 was unusually dry. “Our goal now is to determine relations between Critical Zone structure – as measured in field assessments, pedogenic analyses and geomorphic measurements – and Critical Zone function, as determined from in situ ecohydrology, biogeochemistry and surface water dynamics sensor and sampler measurements,” notes Chorover.

DELIVERING WIDER POLICY BENEFITS

The Jemez River Basin and Santa Catalina Mountains CZO is part of the wider CZO National Program that supports the international scientific community to undertake research by providing infrastructure, data and models that can readily be accessed. It is hoped that each of the CZOs within the CZO National Program will be able to contribute towards building wider knowledge of environmental processes both within the research arena and also providing the science that will underpin environmental policy development. Since the Jemez River Basin and Santa Catalina Mountains CZO team is building their observatory to take advantage of two geologically distinct climate gradients in water-limited mountain ranges, their research will have a specific impact in the arena of climate and water cycle interactions in the semi-arid Critical Zone. “Likewise,” Chorover highlights, “by establishing our CZO along such gradients within large semi-arid watersheds, being the Rio Grande and Colorado Rivers, our research will inform policy on processes that give rise to important freshwater resources of rapidly growing urban populations such as exist in Albuquerque, El Paso and Tucson”.



Critical research

Professor Donald L Sparks and **Drs Anthony Aufdenkampe** and **Lou Kaplan** reveal the progress their cutting-edge project is making on understanding the complex interactions within the Earth's Critical Zone



How has the project benefited from its collaboration with the University of Delaware (UD) and the Stroud Water Research Center (SWRC)?

Both institutions have greatly benefited from partnering on the CRB-CZO, and we expect these benefits to increase. Many scientists from other institutions have already approached us to collaborate because they see substantial added value to performing their research within the field sites and activities of a CZO. The vision that each CZO would serve as a national and international focal point and resource for integrated Earth surface sciences is already materialising.

The project is still in the first half of its funding period. Are you satisfied with its progress to date? What have been the highlights during these first two years of CRB-CZO's existence?

We are making excellent progress on our project. During the first half of the project we have hired some outstanding graduate students and postdocs and forged some exciting and meaningful collaborations. A strong network of team members is in place; we have identified excellent field sites, installed an extensive sensor network that is continuing to expand, added important sampling infrastructure, and established an effective data gathering and management plan.

Are there plans for making the project's results available to policy makers and the public?

We frequently present to, and conduct interviews with, various groups including state agencies, nature conservancies, nature centres, retired faculty and various layperson groups. Specifically, we are building collaborations between research scientists and members of the Christina River Basin Task Force, who are overseeing efforts to preserve the watershed and its water quality for the c. 1 million people who rely on it for drinking water. We are also developing a self-explanatory web portal for the public to visualise our data and models, to understand our results and to share their observations and thoughts (www.wikiwatershed.org).

Firstly, could you offer an insight into the background of this project and its overall goals?

The Christina River Basin Critical Zone Observatory (CRB-CZO) is one of six environmental observatories supported by the US National Science Foundation focusing on how water, atmosphere, ecosystems and soils interact and shape the Earth's surface. The Critical Zone is the Earth's porous near-surface layer, and incorporates everything from the tops of the trees to the deepest groundwater.

The CRB-CZO has the overarching goal of 'integrating the feedbacks between the water cycle, the mineral cycle and the carbon cycle as materials are transported across geophysical boundaries from soils to sea'. We ask whether:

- Processes that mix minerals and carbon are rate limiting to watershed-scale carbon sequestration, chemical weathering and soil production?
- Humans accelerate rates of carbon-mineral mixing and does this result in anthropogenic carbon sequestration significant to local, regional and global budgets?

The Christina River Basin has been studied extensively in the past. How does your research extend beyond work already carried out in this region?

We are performing scientific investigations with a level of disciplinary integration that goes well beyond anything previously carried out. We are bringing cutting-edge, innovative methodologies from each of the individual scientific disciplines involved to bear on our research questions,

exploiting recent advances in open source sensor networking hardware to vastly extend the temporal and spatial coverage of our investigations, and using new cyber infrastructure to share data at an unprecedented level.

In what ways is this Critical Zone Observatory (CZO) and associated research unique from the other five CZOs that form the National Critical Zone Observatory Program?

Humans have emerged as a major geological force on the Earth's surface. The CRB-CZO is the only CZO with an explicit focus on anthropogenic alterations of the Critical Zone. Other strengths of the CRB-CZO, although not necessarily unique, include a connection to the coastal zone, a focus on watershed-scale greenhouse gas budgets, and active development of a wireless sensor network based on powerful, low-cost and easy-to-use open source electronics.

Have you forged relationships with these other CZOs and/or those CZOs beyond US borders?

Absolutely – we participate in monthly discussions with principal investigators from all of the CZOs; moreover, the CZOs have an annual meeting that brings together all researchers to discuss their scientific progress, and many individuals on our team have developed research collaborations with scientists from other CZOs. We were also quite excited to recently co-host Critical Zone scientists from around the world for a workshop on the Design of International CZO Networks in collaboration with SoilTrEC, a European-based effort similar to the CZOs.

Original observations

The **Christina River Basin Critical Zone Observatory** is leading US research into the effects of human impact upon the mineral cycle and its possible effects on carbon sequestration in the Earth's Critical Zone

THE EARTH'S CRITICAL ZONE is the area situated between the lithosphere and the atmosphere; a living, constantly evolving boundary layer where water, atmosphere, ecosystems, and soils interact. It is essential to life on our planet; the complex interactions in the Critical Zone regulate the natural habitat and determine the availability of life sustaining resources, including food production and water quality.

Despite the Critical Zone's importance to terrestrial life, it remains poorly understood: questions remain surrounding how it functions, and how it will change in the future. More specifically, too little is known about how physical, chemical, and biological processes in the Critical Zone are related and at what spatial and temporal scales.

Humans have also had a major geological impact on the Critical Zone. Throughout much of the world, sub-soils are being exposed by aggressive suburban expansions and underground minerals are being excavated and mixed into this chemically and biologically reactive zone. Together with the increasing atmospheric CO₂ level, engineered soil landscapes present scientists with the largest Earth-scale experiment to date. Despite the increasing awareness from diverse disciplines that mineralogy and weathering have a significant bearing upon carbon cycle and storage, the impact of the human accelerated mineral cycle on the carbon flux between lands and the atmosphere remains virtually unknown.

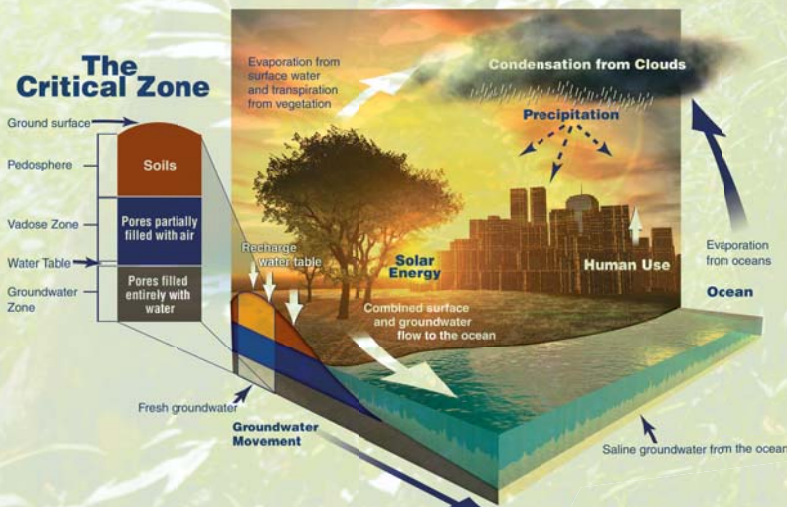
CRITICAL ZONE OBSERVATORIES

In the US, six environmental laboratories called Critical Zone Observatories (CZO) have been established to help determine how the Critical Zone operates and evolves – including

a predictive ability for how it will respond to projected changes in climate and land use. Funded by the National Science Foundation, the CZOs work together on overarching shared goals, but each observatory also focuses on aspects of Critical Zone science that fit the strengths of its investigators and its physical setting. Each CZO consists of a series of field sites within a watershed-scale field area. The sites are instrumented for a variety of hydrogeochemical measurements as well as sampled for soil, canopy and bedrock materials.

The Christina River Basin Critical Zone Observatory (CRB-CZO) was established in 2009, specifically to study mineral and carbon cycles in order to quantify the human impact upon Critical Zone carbon sequestration. Led by Dr Donald L Sparks, the project team at the CRB-CZO is comprised of scientists from the University of Delaware and Stroud Water Research Center (SWRC), who specialise in a diverse range of disciplines: soil science, geochemistry, geomorphology, ecology, hydrology, ecohydrology, environmental engineering, microbiology, biogeochemistry, isotope geochemistry, GIS, and modelling.

CRB-CZO is situated within the 1,440 km² Christina River watershed in South East Pennsylvania and North Delaware. Located in unglaciated Piedmont, the human footprint within the region spans centuries and current land covers include second-growth forest, agriculture, suburbia, urban, commercial and industrial – providing an ideal natural laboratory to study the gradient of human impacts on Critical Zone processes.



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THE CRB-CZO PRINCIPAL INVESTIGATORS

ORGANO-MINERAL COMPLEXATION

Traditionally considered independent, the two major processes governing inorganic and organic aspects of the Critical Zone – the mineral cycle (chemical weathering and mineralogical transformations, mixing into bioactive surface soils, natural versus anthropogenic erosion, colluvial and fluvial transport and burial) and carbon cycle (photosynthetic C-fixation, heterotrophic mineralisation of organic carbon to carbon dioxide and other greenhouse gasses, sequestration in biomass, soils and sediments) – are in fact united by organo-mineral complexation.

Natural organic matter and all the forms of carbon it contains are produced by plants above the soil surface. Fine minerals are weathered out of the bedrock and transported to the surface over time to form soils. The relatively thin soil layer where organic matter and minerals meet and mix supports the growth of most terrestrial and many freshwater ecosystems, including our agricultural systems. Soil surfaces are also where the carbon in a fallen leaf is either returned to the atmosphere as a greenhouse gas or preserved for long periods of time. Sediments provide a similar interface for aquatic systems.

Over the last decade, scientists studying the mechanisms of carbon preservation in soils and sediments have established that one of the most important factors determining the fate of organic carbon in the environment is whether it has been complexed to a mineral surface. It is this key process for stabilising carbon that Sparks' team is interested in: "We define organo-mineral complexation as the suite of chemical mechanisms that bind natural organic matter to minerals such that they are difficult or impossible to separate by physical means alone," Sparks explains. One of the project team's hypotheses is that organo-mineral complexation is limited by the supply of the mineral surface and the mixing of the minerals and organic matter in natural ecosystems.

DATA COLLECTION

A central component of the CRB-CZO project is establishing an environmental sensor network. Much of the team's efforts to date have centred on a single small watershed, which has served as a testbed for this larger network, which will be operational in 2012. To measure water fluxes and storage, the researchers have deployed dozens of pressure/depth transducers in streams and groundwater, as well as soil moisture sensors. To understand biological and geochemical

processes, they have installed temperature, conductivity, redox, oxygen, and carbon dioxide probes in streams and soils. The project's most advanced sensors are submersible UV/Vis diode array spectrophotometers that they can use to quantify suspended solids, nitrate and dissolved organic carbon in streams.

Sparks' team is also using cutting-edge data communication techniques: "An innovative aspect of our sensor network is its foundation on the open source electronics 'Arduino' platform with ZigBee-based radio networking," states Dr Anthony K Aufdenkampe, Co-Lead PI. "With over half a million users worldwide, this approach is robust, easy-to-use and low-cost, all of which allows us to invest our effort and money on widespread deployment of highest quality sensors, rather than on data communication infrastructure."

In addition to the sensor network, the team is also collecting grab samples from streams using automated stream water samplers that can be activated via a mobile phone, together with soil cores, and borings through the soil into the bedrock. They are also using data collected by airborne LIDAR based on two flights over the basin, one under a full tree canopy and one under a bare canopy.

TRANSLATING FINDINGS, BENEFITING ALL

The CRB-CZO team is working hard to ensure its findings are widely disseminated and are benefiting the right people. External investigators may access their datasets through the cyber infrastructure the researchers have created. The SWRC retains two full-time staff to translate CRB-CZO's research into educational programmes for school children, teachers, and citizen and conservation groups. In addition, the University of Delaware has created its own Delaware Environmental Institute (www.udel.edu/denin), which will develop an outreach component.

Existing ties between the University of Delaware, SWRC, and state agencies are being reinforced by the sharing of environmental data. Graduate students conducting research at the CZO are benefiting from the help of the multidisciplinary team of scientists there. The observatory also plans to form a committee, which will evaluate their research activities and make recommendations for site access and the installation of additional field instruments.

The CRB-CZO is at the forefront of scientific research on understanding how human effects on mineral and carbon cycles might affect climate change, and Sparks is confident about what his team can achieve: "By making our measurements in watersheds that include land use and land cover from fully forested to row crop agriculture to active construction, we will be able to assess these effects in a rigorous scientific manner," he asserts. "Also, because the CRB-CZO has an active coastal component, our ultimate goal is to provide an integrated understanding that extends from the headwaters to the estuary."

INTELLIGENCE

THE CHRISTINA RIVER BASIN CRITICAL ZONE OBSERVATORY

OBJECTIVES

To integrate knowledge of water, mineral and carbon cycles to quantify human impact on Critical Zone carbon sequestration – from uplands to coastal zone.

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Delaware Environmental Institute, USA

Stroud Water Research Center, USA

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DR ANTHONY K AUFDENKAMPE is an Associate Research Scientist at the Stroud Water Research Center, leading the Organic and Isotope Geochemistry group studying the processing of terrestrial carbon within aquatic systems.

