Authors’ response: Esurf-2017-36

We appreciate the comments on our paper reviewing the arc of CZ research and proposing a strategy for the future design of an observatory network. We found the reviewers’ comments thoughtful and helpful as discussed below. We also appreciated the comments from outside the U.S.A., specifically reviewers from Sweden (K. Bishop) and Australia (E. Bui), who attest to the importance of the CZ concept.

Both E-Surf reviewers suggested we improve the structure of the manuscript. As pointed out by Tunnicliffe, we brought Section 3 forward in the article. This brings the discussion of the intellectual heritage ahead of the discussion of funding strategies to provide a more logical sequence that emphasizes the evolution of scientific thinking. We also now emphasize the four common elements of CZOs earlier in the paper in the new section incorporating Section 3. We have also revised paragraphs 3 and 4 as suggested by Reviewer #2, so that they describe, in order, the research initiatives and evolution followed by the limits of those research programs and the potential to go beyond those achievements. As requested by Reviewer #2, we also call out Tables 2, 3, and 4 in the manuscript.

Tunnicliffe points out that this re-organization allows the article to better live up to its title. We agree that perhaps the article as initially written and the title were a bit out of sync. After re-organizing and re-emphasizing, we returned to the title of the manuscript to see if a different title was warranted and we decided to keep the title. Tunnicliffe also requested elimination of the use of the word “experiment” to describe the CZ science venture. We have edited out that word and now used a more precise term (enterprise), as suggested.

Another set of words were also the focus of a few more of Tunnicliffe’s comments – paradigm and transformative. “Paradigm” is defined by Merriam Webster as “a philosophical and theoretical framework of a scientific school or discipline within which theories, laws, and generalizations and the experiments performed in support of them are formulated” (accessed at https://www.merriam-webster.com/ on 9-7-17). Scientific paradigms include definitions of what should be studied, the questions of interest, and the broad approach of study. We argue that CZ science is at least a paradigm shift in that it emphasizes that the CZ is one entity and must be investigated in its entirety. Reviewer E. Bui agrees. Therefore, we have included a more complete discussion of why CZ science is a paradigm shift, and we qualify our assertions appropriately. We do respond to Tunnicliffe by using the term paradigm only for the overall CZ science initiative and not for the emergent hypotheses in Section 6, and we emphasize use of the word “transformative” for the CZ enterprise rather than the individual hypotheses in Table 4.

The reviewers had comments on figures that have now been addressed. For example, Tunnicliffe suggested changing Figure 1 to emphasize biological aspects. We have considered possible revisions for Figure 1 and have selected one to replace the earlier version of that figure, because it more clearly integrates biology with the weathering profile and it has been commonly used by the CZ science community to highlight these interactions. Given that both reviewers questioned Figure 3, we have modified the caption by pointing out in our revision that the figure includes sites associated as CZOs and that all the sites shown derive from networks within the U.S.A., Germany, France, and China, noting that some sites in China are co-funded and studied by scientists from the United Kingdom. The sites included are also ones that are registered on SiteSeeker. The RBV and Critex networks (France) include sites outside of Europe. We added this information to the caption: RBV stands for the Réseau des Bassins Versants (Network of Drainage Basins), CRITEX is not an acronym, and TERENO stands for the Terrestrial Environmental Observatories.

We agree completely with the comments about models by Tunnicliffe and Bui. As Table 3 indicates, the initial CZ modeling efforts may be characterized into four groups. The first includes modifications and adoption of existing models to incorporate new couplings between hydrology and biogeochemistry, ecology and biogeochemistry, etc. The second includes identifying and filling critical gaps or knowledge of new processes such as hyporheic exchange, weathering, etc. The third includes development of a new generation of models that takes advantage of emerging streams of high resolution data such as airborne and UAV (unmanned aerial vehicle) based LiDAR and hyperspectral data. The fourth includes coupling between fast and slow processes across many time scales. Slow processes provide the template for the fast response variable, while the accumulative effect of the latter results in the evolution of the former. Both mathematical frameworks and data to support such modeling are still in their infancy. We discuss this in the paper but we do not separate the table explicitly because of the complexity of real distinctions along these lines for many of the models.

Tunnicliffe also writes, “Table 4 is missing any mention of hypotheses related to the social science aspects of the CZ…It would be good to see how this strand of the research fits in!” Likewise, reviewer E. Bui emphasizes that the future NSF network should “address current ‘wicked’ societal problems and help formulate better land development environmental management policies.” We could not agree more. However, the CZO enterprise in the U.S.A. so far has not emphasized social science and no such hypothesis has yet emerged from the community. We emphasize in the revised manuscript that such hypotheses are needed and should be part of the future of the network. For example, in the revision we specifically mention the idea proposed by reviewers P. Shroeder and E. Bui that an urban CZO would be of great interest.

Reviewer #2 points out that “paragraph 7 mentions briefly the publication of numerous datasets (p. 7, l.1) sometimes spanning several decades of measurements…the creation of this repository as well as the website …should be highlighted in the text.” We agree with the reviewer. Tunnicliffe noted that “Table 2 does not back up your point about long-term measurements. It would be more helpful to see the length of these records, rather than a smattering of similar measurements that may or may not relate to broader hypotheses being tested across CZOs.” This reviewer also noted that, “Pg 9, ln 307 makes reference to the ‘extremely long’ duration of the datasets - this could use some quantification.”

We have clarified these points in the revision. In short, the time-series datasets (sensor and sampler arrays, eddy covariance, hydrometeorology, vadose zone and saturated zone aqueous chemistry, etc.) have durations that are roughly equivalent to the age of the CZO sites, determined by the initiation of NSF funding, with the caveat that CZOs have often added new study locations that were not among the original set. Three sites (SSCZO, BCCZO and SSHCZO) have been in operation since 2007, and so their longer-term observational datasets extend roughly over that duration. Three other sites (CJCZO, LQCZO and CRCZO) that initiated operations two years later have measurements dating to 2009, and four newer sites (IMLCZO, CHCZO, RCCZO and ERCZO) have datasets dating to 2013. Therefore, at present, continuous time series datasets range in duration from ca. 4 to 10 years. In addition, however, several of the CZOs are located in sites that provide longer datasets through previous measurement programs. The question of duration of dataset is thus somewhat complex, but we have tried to make this information more transparent in the revision.

Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth

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Abstract. The critical zone (CZ), the dynamic living skin of the Earth, extends from the top of the vegetative~~on~~ canopy through the soil and down to fresh bedrock and the bottom of groundwater. All humans live in and depend on the critical zone. This zone has three co-evolving surfaces: the top of the vegetative~~on~~ canopy, the ground surface, and a deep subsurface below which Earth's materials are unweathered. The ~~US National Science Foundation supported~~ network of nine critical zone observatories supported by the U.S. National Science Foundation has made advances in three broad areas of critical zone research relating to the co-evolving surfaces~~ areas~~. First, monitoring has revealed how natural and anthropogenic inputs at the vegetation canopy and ground surface cause subsurface responses in water, regolith structure, minerals, and biotic activity to considerable depths. This response, in turn, impacts above-ground biota and climate. Second, drilling and geophysical imaging now reveal how the deep subsurface of the CZ varies across landscapes, which in turn influences above-ground ecosystems. Third, several new mechanistic models now provide~~ing~~ quantitative predictions of the spatial structure of the subsurface of the CZ~~ have been proposed~~.

Many countries ~~now~~ fund ~~networks of~~ critical zone observatories (CZOs) to measure the fluxes of solutes, water, energy, gases, and sediments in the CZ and some relate these observations to the histories of those fluxes recorded in landforms, biota, soils, sediments, and rocks. Each U.S. observatory has succeeded in i) synthesizing ~~observations~~ research across disciplines into convergent approaches; ii) providing long-term measurements to compare across sites; iii) testing and developing models; iv) collecting and measuring baseline data for comparison to catastrophic events; v) stimulating new process-based hypotheses; vi) catalyzing development of new techniques and instrumentation; vii) informing the public about the CZ; viii) mentoring students and teaching about emerging multi-disciplinary CZ science; and ix) discovering new insights about the CZ. Many of these activities can only be accomplished with observatories. Here we review the CZO ~~experiment~~ enterprise in the US and identify how such observatories could operate in the future as a network ~~could evolve~~ designed to generate critical scientific insights~~in the future~~. Specifically, we recognize the need for the network to study network-level questions~~s~~, expand the environments under investigation, accommodate both hypothesis testing and monitoring, and involve more stakeholders. We propose a driving question for future CZ science and a "hubs-and-campaigns" model to address that question and ~~that promotes study~~ target ~~of~~ the CZ as one unit. Only with such integrative efforts will we learn to steward the life-sustaining critical zone now and into the future.

1 Introduction

Humans live at Earth's surface – a surface that changes at timescales ranging from milliseconds to millions of years. Understanding how to sustain a growing human population on this changing substrate while simultaneously sustaining diverse ecosystems ~~and the services they provide~~ is a grand challenge for scientists and decision makers (Millenium Ecosystem Assessment Board, 2005; Easterling, 2007). In recognition of the critical nature of Earth's surface, the United States (U.S.) National Research Council defined the zone from the upper vegetative canopy through ground water as the "critical zone" and ~~listed~~ identified study of this "CZ" as one of the *Basic Research Opportunities in the Earth Sciences* (U.S. National Research Council Committee on Basic Research Opportunities in the Earth Sciences, 2001).

While the critical zone was defined in 2001, o~~O~~nly recently has ~~the critical zone~~ it been recognized as a distinct co-evolving entity driven by physical, chemical, and biological processes that sustain life. To tackle the critical zone for the first time as an entity ~~–~~– rather ~~rather~~ than ~~to~~ study pieces of it separately ~~–~~– ~~presents a grand challenge~~is a paradigm shift in science (Fig. 1). ~~Understanding~~ Currently, understanding this zone requires researchers drawn from many traditional disciplines including geology, hydrology, climate science, ecology, soil science, geochemistry, geomorphology, and social science to work in collaboration. In the future, it will be pursued not only by disciplinary researchers but also by new scientists trained to cross disciplines. Critical-zone science uses a wide range of measurements as the foundation for advances in understanding and prediction. Scientists quantify~~measure~~ fluxes of solutes, water, energy, gases, and sediments (SWEGS) as they are today and then compare them to the histories and impacts of those fluxes recorded over geological time in landforms, regolith structure, soils, and sediments. Critical zone scientists also relate these fluxes to natural and anthropogenic drivers as well as to the structure of the critical zone, including biota, soil, and regolith ~~properties~~. In this way, models are developed that can scale CZ properties across the landscape and project the CZ changes across time into the future. From this endeavor has emerged the concept of critical zone science, a new paradigm shift that has been adopted around the world to investigate Earth's surface from canopy to bedrock in its entirety as one integrated unit.

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CZ science ~~is defined by these criteria~~typically has these attributes: i) it targets Earth's surface from canopy through groundwater; ii) it encompasses timescales from milliseconds (or less) to millions of years; iii) it incorporates insights from all relevant disciplines. Some have described CZ science as an attempt to put more geology into watershed ~~and ecosystem~~ science, or the study of the interaction of rocks and ecosystems ~~and biota~~. Each of those descriptors falls short of the full complexity of ~~describing~~ understanding the CZ as ~~as one~~an entity with its own identity.

In the U.S., observatories to study the critical zone have been established by the National Science Foundation (NSF). The physical scope of these ~~some of these~~ U~~.~~S~~.~~ CZOs varies, as some

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are ~~are~~ defined by watershed boundaries, some by land use, others by the range of climate~~ic~~e conditions, and still others by contrasts in lithology or geomorphic history. The common elements are: 1) the focus on the entire above- and below--ground critical zone and its fluxes, 2) documentation of CZ structure, 3) mechanistic process studies, and 4) analysis of the history of the landscape that gave rise to its~~the~~ current structure. This last feature is a crucial aspect of CZOs that distinguishes them from previous studies that typically do not consider “deep time” (i.e., geologic time) and often fail to document the critical zone below the upper soil. Previous papers have described how researchers have grappled ~~at a specific CZO~~ with the establishment of a measurement design at a specific CZO, with the overall data needs of CZOs, ~~(Brantley et al., 2016)~~ and with a modeling ~~design~~ framework that might be used to tackle the complexity of timescales under consideration (Horsbaugh et al., 2008; Duffy et al., 2014; Niu et al., 2014; Brantley et al., 2016).

Over the last ~~After about a~~ decade of study at individual CZOs, cross-CZO science has emerged and begun to unite the observatories into a CZO network with the capacity to test hypotheses across a larger ~~climate, lithology and land-use~~ parameter space than can be~~is~~ represented by any single CZO. As a result, network-level science has begun to emerge and provide opportunities that were not possible in the past. In this paper~~critical zone observatories (CZOs) funded by the U.S. National Science Foundation (NSF)~~, we ~~here~~ review the evolution of CZ science as an interdisciplinary “experiment.” ~~.~~ We ~~In this review of the CZO enterprise, we~~ take stock of successes and weaknesses. The goal of the paper is ~~as a way~~ to ~~map~~ strategize about how to design a better CZO network to maximize future opportunities in CZ science at the levels of the individual observer, the observatory~~ and~~, the network and the broader Earth surface science community. ~~In this paper w~~Specifically, we address the broad question~~e address a broad question~~: what programs and infrastructure are needed by the community to understand the CZ of the future? ~~We explicitly acknowledge that our~~The review is focused on ~~the experiment in the U.S. – we see this approach as an experiment in interdisciplinary and network-level science~~activities and results of this endeavor to date in the U.S.~~like any other, and we focus this paper from that perspective.~~ We acknowledge the many other observatory networks around the world (http://www.czen.org/site_seeker) and invite ~~comments or~~ future papers on how those other networks are constituted and how the various observatory systems can work together. ~~We also welcome input as to how the U.S. system might better fit into the global system.~~

One way to review the U.S. program to date is to summarize performance through quantitative metrics. As manifested today, the program funds nine CZOs situated across a range of landscapes ~~in the U.S.~~ (Fig. 2). In addition, interdisciplinary field observatories that host critical-zone science involve thousands of interdisciplinary investigators in more than 25 nations (Fig. 3) (Giardino and Houser, 2015). Other metrics further highlight how CZ science has energized people and approaches in the U.S. and abroad (Tables 1, 2, 3, 4). Indeed, the term “critical zone” ~~(White and Sharkey, 2016)~~ has been used in 925 papers as of June 2017, in title, abstract, or keyword as recorded in Web of Science. The term has even entered the realm of

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geopolitics (Latour, 2014) and been defined in scientific dictionaries (White and Sharkey, 2016). This is remarkable given that critical-zone science as an idea only dates from 2001. ~~But l~~Less quantifiable, however, is the impact of the idea of the CZ: for example, one country hosting one of the longest-functioning observatory networks in the world (France) is now specifically ~~specifically~~ promoting communication among disciplines and sites. Researchers within that network have pointed to the internationally-emerging paradigm of the ~~, a specific example of the power of the~~ CZ ~~idea~~as a driver for this new level of communication. Thus, quantitative metrics such as those in Table 1 do not fully illustrate the way CZ science has ~~progressed~~impacted science. In the rest of the paper we therefore discuss the ~~arc of ideas,~~ evolution of observatories in environmental science, other mechanisms for studying the CZ, the history of the CZO program, the nine roles of CZOs, and CZO measurements and models. We finish by discussing the strengths and weaknesses of the CZO approach to date~~,~~ and show how network-level understanding is starting to emerge. In the last section we consider an overarching question to drive future CZ science, and we propose a new topology for the CZO network~~an approach for the future of CZ science~~.

~~3~~2 Historical context for ~~E~~environmental observatories and networks

It is useful to place the CZ enterprise broadly into the context of environmental science. The differentiated scientific disciplines largely did not yet exist until the 1900s, and the earliest natural scientists therefore tended to be multi-disciplinary (e.g. Forbes, 1887; CFIR CSEPP, 2005; Warkentin, 2006; Berner, 2012; Riebe et al., 2016). These~~In addition to the three types of initiatives summarized in the last section, environmental scientists~~ researchers early on began to articulate ~~have long recognized~~ the need for place-based, integrative science. This has led to ~~.~~ ~~This recognition has led to~~ a rich ~~a “deep”~~ history ~~and a~~ of ~~diverse set of~~ diverse, place-based, experimental, and long-term observation sites in the U.S. and world.

~~Early on, m~~Many of these observatories were established to investigate the impacts of specific land use activities. One of the first was the Rothamsted Experimental Station in Harpenden, England, founded in 1843 to study the effects of fertilizers on crops. Not until 1910 did ~~Within the U.S.,~~ the concept of using paired watersheds to investigate the hydrologic and geomorphic impacts of land use treatments within the U.S. begi~~an~~ ~~at Watson Wheel Gap, CO in 1910, where~~ when a pair of small instrumented catchments were instituted for monitoring~~ed~~ to evaluate changes in stream flow and sediment yield at Watson Wheel Gap, Colorado (Van Haveren, 1988).

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As human population and land use increased, researchers began to ~~write about the need to~~ compare ~~long-term measurements at both~~ pristine sites to ~~and~~ human-impacted sites, and began emphasizing the need for ~~-~~long-term measurements (Leopold, 1962). The U.S. Geological Survey thus developed a hydrologic benchmark network (HBN) of 57 basins (Cobb and Biesecker, 1971) to make long-term hydrologic measurements. The mandate of the HBN was expanded in 2011 to include long-term observations not only of stream flow and water quality but also of soil chemistry and aquatic ecology ~~monitoring in 2011~~ (McHale et al., 2014). Thirty-seven hydrologic benchmark watersheds are still maintained (Mast, 2013), but the original vision to also characterize vegetation and geology has remained unfulfilled.

The paired-watershed approach pioneered in Watson Wheel Gap, C~~O~~olorado, was replicated much later in many other locations in the U.S., including Coweeta Hydrologic Laboratory (North Carolina), Hubbard Brook (N~~H~~ew Hampshire), Reynolds Creek Experimental Watershed (Idaho), ~~Coweeta Hydrologic Laboratory (NC),~~ and the H.J. Andrews Experimental Forest (O~~R~~regon) among others. These pioneer sites, in turn, led to the establishment of over 70 Experimental F~~f~~orests and ~~r~~Rangelands as sites ~~sites~~ that focus~~ed~~ on fundamental and applied questions spanning hydrology, silviculture, soil science, and climate research (Lugo et al., 2006).

In the early 1980s, as academic scientists pointed out the difficulties of answering questions about long-term natural processes given the realities of short-term funding (Bormann and Likens, 1979; Callahan, 1984), the U.S. National Science Foundation Directorate of Biological Sciences created the Long-Term Ecological Research (LTER) program to carry out observation-based research across a network of sites that spanned the major biotic regions of North America. These efforts were aided by early work of the U.S. Forest Service to understand watershed hydrology (Swank and Crossley, 1988). The LTER effort was initiated predominantly by ecosystem ecologists asking questions about organisms with long life cycles, including how they are maintained by natural water and nutrient fluxes in the face of ~~long-term~~ acute environmental changes that are long-term as well as episodic~~,~~ ~~acute environmental changes~~ (Dodds and al., 2012). Although not exclusively based on the study of watersheds as pioneered in the late 1960s (Bormann and Likens 1967), many LTERs follow a model that emphasizes the study of energy, water, and material flows through a watershed (Hynes 1975). ~~Going forward~~As of 2017, the LTER network contains 28 LTERs and is beginning to emphasize the need ~~aims~~ to incorporate ~~consideration of~~ social science (LTER Network Office, 2011).

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A big step was taken in 1991 toward incorporating geology into these largely water-land use-ecology observatories when the U.S. Geological Survey inaugurated the Water, Energy and Biogeochemical Budgets (WEBB) program. WEBB targe~~t~~ted interactions among water, energy, and biogeochemical fluxes in five sites chosen at least partly ~~by~~on the basis of -their inherent geological characteristics ~~character~~ and relatively pristine ~~nature~~condition.

Then, in 2008, another long-term research program was ~~called for~~ envisioned by agricultural researchers (Robertson et al. 2008). This vision~~,~~ resulted~~ing~~ in the establishment of the Long-Term Agroecosystem Research (LTAR) program in 2011. This network, today including 18 LTARs, promotes long-term agricultural research facilities, experiments, and watershed-based studies focused on sustaining agriculture and increasing crop yields under changing climate conditions while minimizing or reversing any adverse environmental impacts (http://www.tucson.ars.ag.gov/ltar/).

The most recent addition to the development of observatories in the U.S. is the National Ecological Observatory Network (NEON). NEON is a ~~nation~~U.S.-wide, distributed observatory that aims to understand and forecast the impacts of climate change, land use, and invasive species on ecology and ecosystem fluxes by providing a research platform for investigator-initiated sensors, observations and experiments that can provide ~~i)~~ consistent, continental, long-term, multi-scaled data~~, and ii) a research platform for investigator-initiated sensors, observations and experiments~~ (Loescher et al., 2017). NEON has 84 sites across the U.S. Like LTER, NEON is a program funded by the Directorate of Biological Sciences at NSF to study ecological change (Golz et al., 2016).

As in the U.S., international observatory networks have also grown, many for substantially the same reasons that they grew in the U.S. – to study land use, water, and ecology. In at least one country (France), a network (OZCAR: Observatoires de la Zone Critique: applications et recherche) emphasizes individual disciplines at each observatory and provides as much as 50 years' worth of data to enable research in some sites. The long-term, place-based ecological research that was pioneered by the ~~U.S.A.~~ LTER network in the U.SA. has also been adopted by the broader international community in the International LTER (ILTER) network (Vanderbilt and Gaiser, 2017). Today, the European Commission is promoting an approach to develop a European Research Infrastructure in the form of a network associating CZOs, LTERs and LTSERs. Here, LTSER stands for Long Term Socio-Ecological Research, i.e., a network that also incorporates questions from social science. Indeed, many of the European countries maintain strong observatory infrastructures that are much more tightly linked with local stakeholders than observatories in the U.S. This may result from the lack of truly "natural" territories in Europe, given the long history of development on the continent but also the willingness to co-construct research questions with stakeholders to build a sustainable environmental future.

~~2~~3 Non-observatory approaches used to study the CZ

Just as observatory science was beginning with the Watson Wheel Gap observatory in the early 1900s, scientists also began to focus on portions of the Earth system that could be understood in a reductionist sense (Riebe et al., 2016). ~~We start by a very brief backward look to summarize approaches to investigate the CZ. Here, we do not seek to exhaustively summarize history but only to place the CZO experiment within a context. For example, the scientific disciplines of today largely did not yet exist until the early 1900s, and the earliest natural scientists therefore tended to be multi-disciplinary~~ (e.g. Forbes, 1887; CFIR CSEPP, 2005; Warkentin, 2006; Berner, 2012)~~. It was not until the 1900s that scientists began to focus on portions of the Earth system that could be understood in a reductionist sense (Riebe et al., 2016). It is instructive to consider the approaches to studying CZ science that have emerged during this latter period.~~

~~First, as scientific disciplines developed throughout the 20th century,~~ Eventually, s~~s~~mall-grant funding to single investigators or small teams became the dominant mechanism to fund research

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to explore questions about the CZ~~ in the U.S~~. This targeted approach further emphasized reductionism and served to grow ~~weventually promoted~~ the individual disciplines of geochemistry, geobiology, geomorphology, hydrology, soil science, ecology, meteorology, and others. ~~Such d~~Disciplinary growth ~~allowed scientific endeavors~~ in turn allowed relatively defined “monodisciplinary” paradigms to mature and led to the ~~, as exemplified in the~~ proliferation of disciplinary journals~~ published worldwide~~. For example, Web of Science currently indexes 225 journals in the fields of environmental sciences, 184 in ~~multidisciplinary~~ geosciences, and 150 in ecology, with some journals cross-reported in more than one category.

Through smaller funded projects, many different types of measurements were made. However, the measurements were completed at different sites and integration of observations into models was difficult to impossible. Advances in studying Earth’s surface tended to be uneven because different sites were targeted and coordination among disciplinary approaches was lacking. Such fragmentation accentuated the need for observatories. Other mechanisms were also needed, however, as questions about environmental impacts on human health grew in the U.S. throughout the 1970s (CFIR CSEPP, 2005). ~~Second, as questions about landforms, soils, water, and biota at Earth’s surface sharpened,~~ Funding agencies began seeking teams of researchers to pursue ~~needs arose to fund multi-investigator~~ campaigns – concerted, multi-investigator, multi-year projects – targeting ~~specific~~ focused hypotheses about landforms, soils, water, biota, in addition to human health~~questions~~. Such ~~Campaigns were concerted, multi-investigator, multi-year projects designed to understand a particular process or set of questions. Perhaps the largest and most global example of a “campaign” was~~ campaigns culminated in global efforts such as the Millenium Ecosystems Assessment (Millenium Ecosystem Assessment Board, 2005) and the International Geosphere-Biosphere Program (IGBP). The latter initiative ~~that~~ engaged 10,000 scientists from more than 20 disciplines and 80 countries ~~around the world~~ (CFIR CSEPP, 2005; Millenium Ecosystem Assessment Board, 2005). ~~In 1970, questions about environmental problems and human health grew in the U.S. and drove more funding for both small-investigator and campaign grants (CFIR CSEPP, 2005).~~ ~~Perhaps the largest and most global example of a “campaign” was the International Geosphere-Biosphere Program (IGBP) that engaged 10,000 scientists from more than 20 disciplines and 80 countries around the world (CFIR CSEPP, 2005).~~

Eventually, a~~ third~~ nother type of funding ~~paradigm~~ mechanism to study the CZ emerged in the U.S. ~~also grew hand in hand with~~ alongside observatory, single-investigator, and campaign-style science. Specifically, centers of excellence were funded ~~in the U.S.~~ to draw together ~~expertise~~ scientists into institutions to focus on specific problems or approaches. One impetus for this was the inauguration in 1987 ~~by~~ of the NSF Science and Technology Center program. This effort eventually supported two centers of especial relevance to critical zone research: SAHRA (Sustainability of ~~semi~~Semi-Arid Hydrology and Riparian Areas) and NCED (National Center for Earth-surface Dynamics). –NCED (2002 to 2012) focused on developing a quantitative, predictive Earth-surface science by integrating geomorphology, ecology, hydrology,

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Other examples of institutionalized centers of excellence also were important in developing aspects of CZ science. For example, the Community Surface Dynamics Modeling System (CSDMS; http://csdms.colorado.edu/wiki/Main_Page) is building and promoting a library of models for various Earth surface processes ~~and supports~~ by supporting a broad community of modelers. The National Center for Airborne Laser Mapping (NCALM, established in 2003) provides research-quality airborne light detection and ranging (LiDAR) observations to the community. Another example is the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI; https://www.cuahsi.org/), which aims to advance hydrologic sciences broadly across the U.S. and its member universities. Other centers of excellence have been established to promote use of instrumentation such as the NSF-funded Purdue Rare Isotope Measurement Laboratory (PRIME Lab), a dedicated research and service facility for accelerator mass spectrometry (AMS) including measurement and interpretation of cosmogenic isotopes.

~~3 Environmental observatories and networks~~

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~~In addition to the three types of initiatives summarized in the last section, environmental scientists have long recognized the need for place-based, integrative science. This recognition has led to a “deep” history and a diverse set of place-based, experimental, and long-term observation sites. Early on, many of these were established to investigate impacts of specific land use activities. One of the first was the Rothamsted Experimental Station in Harpenden, England, founded in 1843 to study the effects of fertilizers on crops. Within the U.S., the concept of using paired watersheds to investigate the hydrologic and geomorphic impacts of land use treatments began at Watson Wheel Gap, CO in 1910, where a pair of small instrumented catchments were monitored to evaluate changes in stream flow and sediment yield (Van Haveren, 1988).~~

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~~As human population and land use increased, researchers began to write about the need to compare long-term measurements at both pristine and human-impacted sites (Leopold, 1962). The U.S. Geological Survey thus developed a hydrologic benchmark network (HBN) of 57 basins (Cobb and Biesecker, 1971) to make long-term hydrologic measurements. The mandate of the HBN was expanded to include observations not only of stream flow and water quality but also soil chemistry and aquatic ecology monitoring in 2011 (McHale et al., 2014). Thirty-seven hydrologic benchmark watersheds are still maintained (Mast, 2013), but the original vision to also characterize vegetation and geology has remained unfulfilled.~~

~~The paired-watershed approach pioneered in Watson Wheel Gap, CO, was replicated much later in many other locations in the U.S., including Hubbard Brook (NH), Coweeta Hydrologic Laboratory (NC), and the H.J. Andrews Experimental Forest (OR) among others. These pioneer sites, in turn, led to the establishment of over 70 forest and rangeland sites that focused on fundamental and applied questions spanning hydrology, silviculture, soil science, and climate research (Lugo et al., 2006).~~

~~In the early 1980s, as academic scientists pointed out the difficulties of answering questions about long-term natural processes given the realities of short-term funding (Bormann and Likens, 1979; Callahan, 1984), the U.S. National Science Foundation Directorate of Biological Sciences created the Long-Term Ecological Research (LTER) program to carry out observation-based research across a network of sites that spanned the major biotic regions of North America. These efforts were aided by early work of the U.S. Forest Service to understand watershed hydrology (Swank and Crossley, 1988). The LTER effort was initiated predominantly by ecosystem ecologists asking questions about organisms with long life cycles, including how they are maintained by natural water and nutrient fluxes in the face of long-term as well as episodic, acute environmental changes (Dodds and al., 2012). Although not exclusively based on the study of watersheds as pioneered in the late 1960s (Bormann and Likens 1967), many LTERs follow a model that emphasizes the study of energy, water, and material flows through a watershed (Hynes 1975). Going forward, the LTER network contains 28 LTERs and aims to incorporate consideration of social science (LTER Network Office, 2011).~~

~~A big step was taken in 1991 toward incorporating geology into these largely water-land use-ecology observatories when the U.S. Geological Survey inaugurated the Water, Energy and Biogeochemical Budgets (WEBB) program. WEBB targetted interactions among water, energy, and biogeochemical fluxes in five sites chosen at least partly by their inherent geological character and pristine nature.~~

~~Then, in 2008, another long-term research program was called for by agricultural researchers (Robertson et al. 2008), resulting in the establishment of the Long-Term Agroecosystem Research (LTAR) program in 2011. This network, today including 18 LTARs, promotes long-term agricultural research facilities, experiments, and watershed-based studies focused on sustaining agriculture and increasing crop yields under changing climate conditions while minimizing or reversing any adverse environmental impacts (http://www.tucson.ars.ag.gov/ltar/).~~

~~The most recent addition to the development of observatories in the U.S. is the National Ecological Observatory Network (NEON). NEON is a nationwide, distributed observatory that aims to understand and forecast the impacts of climate change, land use, and invasive species on ecology by providing i) consistent, continental, long-term, multi-scaled data, and ii) a research platform for investigator-initiated sensors, observations and experiments (Loescher et al., 2017). NEON has 84 sites across the U.S. Like LTER, NEON is a program funded by the Directorate of Biological Sciences at NSF to study ecological change (Golz et al., 2016).~~

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~~As in the U.S., international observatory networks have also grown, many for substantially the same reasons that they grew in the U.S. – to study land use, water, and ecology. In at least one country (France), a network (OZCAR: Observatoires de la Zone Critique: applications et recherche) emphasizes individual disciplines at each observatory and provides as much as 50 years' worth of data to enable research in some sites. The long-term, place-based ecological research that was pioneered by the U.S.A. LTER network has also been adopted by the broader international community in the International LTER (ILTER) network (Vanderbilt and Gaiser, 2017). Today, the European Commission is promoting an approach to develop a European Research Infrastructure in the form of a network associating CZOs, LTERs and LTSERs. Here, LTSER stands for Long Term Socio-Ecological Research. Indeed, many of the European countries maintain strong observatory infrastructures that are much more tightly linked with local stakeholders than observatories in the U.S. This may result from the lack of truly "natural" territories in Europe, given the long history of development on the continent but also the willingness to co-construct research questions with stakeholders to build a sustainable environmental future.~~

4 The CZO ~~network~~program

~~Clearly, this history shows how the pantheon of observatories has long targeted land use, water, ecosystems, and agriculture. None of these efforts were intended to incorporate~~ Even with this variety of funding mechanisms for Earth and environmental science, no concerted nationwide effort emerged to tackle questions and to train students to target the CZ as one entity, incorporating the deep geological underpinnings and long-timescale perspectives. ~~that have come to be the hallmarks of CZ science. More specifically, none of these observatories targeted the entire CZ as one entity. As such~~As a result, ~~this~~ the ~~place-based~~ environmental science that developed often ~~was forced to use~~ had to rely on statistical approaches to explain variability instead of developing more fundamental explanations ~~that was caused by~~ based on underlying geological heterogeneity and its origins. Recognizing ~~this~~ the need to emphasize the geological underpinnings of place-based science in the late 2000s, researchers within the water, soil, geochemistry, and geomorphology communities began articulating a need for integrated science across the entire zone from canopy to bedrock to incorporate the full significance of the underlying geology (Anderson, 2004; Brantley et al., 2006; Chorover et al., 2007; U.S. Committee on Integrated Observations for Hydrologic and Related Sciences, 2008; U.S. Steering Committee for Frontiers in Soil Science, 2009; U.S. National Research Council, 2010; Banwart et al., 2011; Committee on New Research Opportunities in the Earth Sciences at the National Science Foundation, 2012; White and Sharkey, 2016). ~~These researchers also recognized that advances in studying Earth's surface were fragmented precisely because investigators typically targeted many different sites without coordination among disciplinary approaches. Under the paradigm of small funded projects, different types of measurements were made but they were completed at so many different sites that integration of observations into models was difficult to impossible.~~

Eventually the need to study the CZ as one integrated entity resulted in the NSF program establishing the Critical Zone Observatory program in 2007 (White et al., 2015). ~~By 2007~~In this initial phase, three CZOs ~~had been~~ were funded (Anderson et al., 2008). Two years later, three more CZOs were funded. By 2013 this number had grown to nine observatories supported through a competitive selection process. In addition to the expansion of sites in 2013, a CZO National Office (NO) was established by NSF in 2014 through a~~n NSF~~ competitive process, with the intent of ~~establishing~~ providing the CZO Network ~~to provide~~ with an administrative ~~network~~ structure for furthering ~~the network and function~~ coordination (White et al., 2015). The number of CZOs has remained stable through 2017.

Inauguration of the CZO program implicitly defined the term “critical zone observatory” to be distinct within the long history of observatories in the US and abroad as an observatory that promotes study of the entire CZ as one entity. As implemented today, CZOs are sites or closely connected sets of sites with no required size or specified range of conditions. In fact, the physical scope of a CZO is set only by the fundamental questions driving the establishment of the observatory. A fundamental characteristic of a CZO is that it is able to operate over a long enough period to quantify ~~thoroughly~~ controlling mechanisms thoroughly and to capture temporal trends that ~~may~~ reveal ~~further~~ how the critical zone operates. ~~Another~~ Two more characteristics of a CZO ~~is~~ are that it is amenable to study by many disciplines and that it ~~.~~ integrates understanding of long- and short-timescale phenomena. Finally, each ~~Importantly, a~~ CZO ~~is~~ operates as an adaptive and agile hypothesis-testing machine, not simply a monitoring program.

~~The physical scope of some U.S. CZOs are defined by watershed boundaries, some by land use, others by the range of climate conditions, and still others by contrasts in lithology or geomorphic history. The common elements are: 1) the focus on the entire above- and below-ground critical zone and its fluxes, 2) documentation of CZ structure, 3) mechanistic process studies, and 4) analysis of history of the landscape that gave rise to the current structure. This last feature is a crucial aspect of CZOs that distinguishes them from previous studies that typically do not consider “deep time” (i.e., geologic time) and often fail to document the critical zone below the soil. Previous papers have described how researchers have grappled at a specific CZO with the establishment of a measurement design (Brantley et al., 2016) and modeling design (Duffy et al., 2014; Niu et al., 2014).~~ ~~I~~As~~n addition to hypothesis-testing,~~ CZOs ~~developed~~~~evolved~~developed in the U.S., they began to play nine important ~~accomplish nine additional~~ ~~emergent~~ roles within the environmental scientific endeavor. These aree~~to advance CZ science~~~~, as~~ ~~described in the next section,~~ described in the next section.

5 The nine emergent roles of CZOs

Here ~~we highlight~~ the nine important roles ~~that can only be accomplished at~~ of an observatory are described ~~and amplify the description of each role~~ with examples of scientific results from across the CZO network today.

First, CZOs act as *synthesizers of interdisciplinary research into convergent approaches* at one specific site that lead to ~~emergent~~ novel understanding and ultimately result in more deeply-informed ~~process-based models~~generalized and predictive understanding (e.g.Rasmussen et al., 2011b; Kumar et al., 2017, in review) (Rasmussen et al., 2011a). In other words, observatories induce scientists from different disciplines to make measurements using different disciplinary approaches at the same location instead of making them at disparate sites, driving cross-disciplinary understanding ~~that crosses the boundaries of disciplines~~ in describing CZ function (Hynek et al., 2016; Sullivan et al., 2016; Yan et al., 2017; Chen et al., 2017 in press). ~~To date~~At first, much of the synthesis ~~has~~ crossed only two disciplines at a time: for example, several papers ~~have~~ emphasized how geomorphological concepts related to erosion must be incorporated to understand chemical weathering, and vice versa (Rempe and Dietrich, 2014; Riebe et al., 2016). Likewise, researchers have related tree roots to water cycling (Vrettas and Fung, 2015). Now, researchers are targeting ~~But many puzzles remain concerning~~ multi-disciplinary aspects of CZ entities~~, and much effort is currently focusing on such frontiers~~. For example, at the Calhoun CZO, where the South Carolina landscape was severely eroded by cotton farming, logistic regression models treat market and policy conditions in the context of topographic characteristics (Coughlan et al. 2017). ~~In another example, distributed CZO data were used to develop a predictive framework linking regolith structure, root-zone storage and vegetation to dry periods (Klos et al., 2017, in review). CZOs have~~By ~~fostered~~ fostering measurements from all disciplines in centralized places~~ and this is the first step toward addressing broader multi-disciplinary models describing CZ function~~, CZOs are discovering not only how to cross disciplines but how individual ~~such~~ disciplines can converge~~(Brantley et al., 2017, in press; Holbrook et al., 2017, in review)~~.

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Second, CZOs provide *stable platforms for long-term measurements* ~~*made over long-term durations*~~ (Table 2). Some ~~of the~~ datasets synthesized by CZOs are now available ~~at CZOs are extremely long~~~~decadal to multi-decadal in duration~~for decades or several decades~~, enabling the testing of effects of inter-annual climatic variation effects as well as longer-term climate or land-use trends~~. For example, the Reynolds Creek CZO recently published 31 years of hourly data that ~~is~~ are spatially distributed at 10 m resolution for air temperature, humidity, and precipitation ~~amount and phase across the 239 km^2 Reynolds Creek Experimental Watershed~~ (Kormos et al., 2016) and a ~~. Reynolds also published another~~ 10~~-~~-year data set that spans the rain-snow transition ~~zone~~ (Enslin et al., 2016). Similarly, ~~using water balance, climate and satellite datasets, Zapata-Rios et al. (2016) demonstrated~~ decreasing trends in water and energy influx in the Jemez CZO ~~to the CZ~~ over the past 30 years were ~~in the Jemez CZO and~~ recently related to ~~discussed the implications of these long-term trends for~~ CZ structure ~~development~~(Zapata-Rios et al., 2016). Major changes in soil biogeochemistry have been documented by Calhoun CZO researchers over 50-years of reforestation in fields cultivated for cotton (Mobley et al., 2015). T~~as inferred from present day CZ structural datasets~~hat CZO also spearheads an effort to recover archived data from three eroded watersheds that were farmed from the late 1940s to 1962 – as well as to re-instrument the catchments.~~.~~ ~~-~~Many other multi-year~~of the long-term~~ ~~datasets made at CZOs are~~ measurements ~~that are~~ common to all CZOs ~~and~~ enable ~~have been designed to test the hypothesis that new understanding will~~ hypothesis-testing~~emerge about processes and function from such cross-cutting data~~. For example, characterization of dissolved organic matter (DOM) ~~coordinated~~ measured with similar methodology across five CZOs revealed a strong role for CZ structure in setting the origin, composition and fate of DOM in streams (Miller et al., 2016). In another example, a coordinated effort emerged to measure and understand the relationships among ~~chemical species'~~solute concentrations and water discharge in streams (e.g. Kirchner, 2003; Godsey et al., 2009). ~~This led to papers published by CZ scientists in a~~A special issue on the topic ~~of *Water Resources Research*~~ (Chorover et al., 2017, in press) is pointing the way toward the use of ~~. The goal now is to use CZO~~ knowledge of subsurface structure to explain concentration-discharge behavior *a priori* ~~for other settings~~.

Third, CZOs act as *a stimulus and test-bed for modelling and prediction*. Modeling the CZ ~~poses a~~is a unique challenge in that models must ~~of~~ address ~~ing~~ the coupling across ~~a very broad range of~~ time scales from seconds to millennia ~~weather driven event dynamics to~~ (Table 3). To tackle this challenge, CZOs are both adapting existing models and developing new models. For example, one CZO is developing a hierarchy of modules to describe processes that occur over seconds to millennia (Duffy et al., 2014). ~~millennium scale geologic formation. This intertwining of functional outcome at the short time scale resulting from the form or structure formed at the long time scale, within the context of specific hypothesis creates unique challenges of coupling across many time scales within a modeling framework. At the same time, availability of novel measurements in space, time and depth is enabling CZOs to ask new questions that were not possible before. To address these challenges and opportunities, CZOs have been adapting existing models or developing new ones to answer questions that seem pertinent to a specific CZO or have applicability across CZOs.~~For long timescale processes~~.~~ ~~For example~~, almost every CZO has proposed models of ~~soil and~~ regolith formation, and many are summarized ~~several have been described in publications~~ in a special issue ~~of *Earth Surface Processes and Landforms*~~ (Riebe et al., 2016). ~~Many~~ At the shorter timescales, ~~of the~~ standard water or coupled land surface-air models have ~~also~~ been tested and new modules ~~have been~~ developed ~~at CZOs~~(Table 3) ~~(Table 3)~~. ~~One CZO has contributed a hierarchy of numerical models for understanding processes that occur over microseconds to millennia (Duffy et al., 2014).~~ To exploit high resolution data such as LiDAR and hyperspectral measurements, modelling efforts ~~Another CZO has contributed a model to exploit emerging high resolution data such as from LiDAR resolution dataand hyperspectral instruments~~ explore ~~to understand the role of~~ micro-topographic and vegetation ~~variability in controlling~~ controls on soil moisture (Le et al., 2015; Le and Kumar, 2017) ~~and~~ as well as biogeochemical changes in agricultural landscapes (Woo and Kumar, 2017) ~~in agricultural landscapes~~. Researchers ~~at another CZO~~ have likewise developed a ~~rigorous~~

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energy-balance snowmelt model that is now being used with ~~airborne LiDAR (Painter et al., 2016) and other~~ remotely sensed data for water supply forecasting (Painter et al., 2016). ~~Work at the Luquillo CZO in Puerto Rico has allowed testing of models for stream channel self-organization at many other locations (Phillips and Jerolmack, 2016).~~ In other integrative efforts, researchers are ~~investigating and~~ modelling how hydraulic conductivity, root water uptake efficiency, and hydraulic redistribution by plants ~~combine to~~ sustain evapotranspiration through dry seasons (Quijano et al., 2012; Quijano et al., 2013; Vrettas and Fung, 2015). Work at the Luquillo CZO has supported interpretations of the controls on bedload grain size and channel dimensions for rivers (Phillips and Jerolmack, 2016). Researchers at the Calhoun CZO are using distributive models to explore relationships between topographic variations and the landscape's capacity to serve as an atmospheric carbon source or sink (Dialyanis et al., 2015).

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Fourth, CZOs act as *baselines to understand and teach about the impact of catastrophic events*. For example, two western ~~USA~~ CZOs in the U.S. have studied the impacts of wildfire~~s were studied~~ on soil microbiota (Weber et al., 2014), sediment yields (Pelletier and Orem, 2014), snow accumulation (Harpold et al., 2014), and water quality (Murphy et al., 2012; Reale et al., 2015)~~ at two CZOs in the western USA~~. Likewise, effects of the 2013 Colorado Front Range storm (Gochis et al., 2015) on debris flows (Anderson et al., 2015), soil moisture (Ebel et al., 2015), cosmogenic radionuclides (Foster and Anderson, 2016), and concentration-discharge behavior (Rue et al., 2017) were studied at the Boulder Creek CZO. A flash flood within ~~a research catchment of~~ Boulder Creek CZO in 2016 instigated analysis of Horton overland flow in these landscapes (Klein et al., 2017). CZOs that experience catastrophic events use the baseline data captured before the event to place the ~~scope of the~~ impact into perspective. An additional attribute is that s~~S~~uch natural disasters ~~also~~ engender public interest in research: ~~Boulder Creek CZO~~ research on the 2013 Colorado Front Range storm from the Boulder Creek CZO ~~has been featured in radio, press, and public forums~~and wildfire~~ and wildfire~~ research from three CZOs ~~has been~~ has been featured in radio, press, and public forums~~featured in outreach from three CZOs~~. The important role of observatories in recording catastrophic events was reinforced by Hurricanes Irma and Maria, which brought winds up to 250 km h^{-1} and enormous rainfall to the island of Puerto Rico in September 2017. The Luquillo CZO quantified winds, rains, and stormflows and will document Maria's impacts to forest canopies, accelerated tree throw, and mass hillslope movements for many years to come.

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Fifth, CZOs act as *the organizing design for systematic campaigns to investigate process-based mechanisms* ~~in~~ across ~~various CZ environments~~different types of CZ. One example of this is the initiative in which every CZO in the U.S. pursued geophysical measurements. Many papers have been published exemplifying this approach to map out the subsurface architecture (Befus et al., 2011; Holbrook et al., 2014; Orlando et al., 2015; Olyphant et al., 2016). ~~Increasingly~~Now, geophysicists ~~are~~ travel~~ling~~ among CZOs to image the subsurface with a battery of instruments ~~and evolving approaches that reveal~~ to image the below-ground landscape

(St. Clair et al. 2015). In another example, after ~~one CZO~~the Boulder Creek CZO began emphasizing slope aspect as a useful natural experiment to examine controls on CZ architecture and function in 2009~~.~~, ~~This early abstract led to~~ similar analyses at other CZOs led to ~~and emerging~~highlighted ~~concepts of~~ linkages ~~between~~ among aspect, water, biota, regolith structure, and episodic events (West et al., 2014; Ebel et al., 2015; Pelletier et al., 2017)~~, including cross-CZO collaboration on theory (Pelletier et al., in press)~~. Finally, a deep drilling project~~s~~ ("drill the ridge") ~~were~~ was proposed and then pursued at many CZOs, and these data in turn led to a special issue describing regolith formation (Riebe et al., 2016). Successful campaigns have also been mounted to investigate mountain snow and water balance (Harpold et al., 2014)~~, and the distribution of micro-organisms in soils (Griffin et al., 2017, in review)~~.

Sixth, CZOs act as *catalysts for the development of new techniques and instrumentation* ~~*from all disciplines*~~ which can then be tested globally. –For example, at the Eel River CZO, a unique vadose zone monitoring system (VMS) has been installed consisting of ~~19 m long~~ holes drilled ~~along contour of~~ into a hill~~slope~~ at 55° relative to the horizontal ~~and filled with sleeves with~~ to monitor~~s~~ for temperature, pressure, and electrical conductivity. Th~~is is giving access to~~e VMS probes the generally inaccessible deep vadose zone ~~in the weathered bedrock~~ to test reactive transport models incorporating gas and water chemistry (Druhan et al., 2017). At another CZO, ~~rainfall simulation~~ experiments designed -to improve management practices for erosion have elucidated controls on the ~~ratio of the~~ concentration of carbon in eroded sediment ~~to that of~~ and original soil ~~in order to improve management practices for erosion~~ (Papanicolaou et al., 2015). One CZO is exploring weathering reactions through ~~pioneering~~ the use of neutron scattering (NS) to analyze pores as small as nanometers in rocks ~~and how they contribute to weathering reactions~~ (Navarre-Sitchler et al., 2013). Water-balance instrumentation using robust wireless-sensor networks, developed at the Southern Sierra CZO (Kerkez et al., 2012), has been extended to the river-basin scale (Zhang et al., 2017), and is being deployed at other locations across the U.S. An approach developed to scale annual evapotranspiration measured at flux towers across the broader forested landscape of the Sierra Nevada (Goulden et al., 2012) is also being applied to flux-tower sites and forested areas across the western U.S.

Seventh, CZOs serve as *hubs for informing regional resource-management decisions, and for educating the public about societally relevant problems*. For example, measurements of evapotranspiration made at one CZO and scaled across the Sierras provide a basis for estimating sustainable forest densities today and into the future when ~~in both current~~ the climate ~~and a~~ will be warmer~~,~~ and drier~~d~~ ~~climate~~ (Goulden and Bales, 2014). ~~While it is accepted that the overly dense forests that are in part the result of decades of fire suppression are at high risk of wildfire and drought-induced mortality, action to restore forests remains slow. This work has major implications for forest restoration and payment for ecosystem services.~~ Research on water resources is routinely communicated to water managers in California and the intermountain west by the Southern Sierra ~~and Boulder Creek~~ CZO~~s~~ through briefings, workshops and data products. Results from Catalina-Jemez CZO studies of wildfire impacts on watershed-scale sediment

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transport are ~~now~~also being considered in the development of forest management strategies in ~~AZ and NM~~two states. Research on snowpack and water resources by the Boulder Creek CZO ~~for water managers in Colorado, Utah and Wyoming~~ has similarly been communicated in a series of workshops for water managers in Colorado, Utah and Wyoming ~~co-organized by the Boulder Creek CZO~~ in 2015. In other parts of the country, the Eel River CZO ~~team~~ is documenting controls on the ~~summer~~ spread of cyanobacteria in the Eel River, and information is disseminated in ~~which has led to~~ biannual gatherings of students, agency members, native Americans, and practitioners ~~to learn to recognize algae types~~. IMLCZO is developing ~~and disseminating~~ a series of courses ~~to~~ for crop advisors ~~through the extension program~~ in the US agricultural Midwest. Finally~~Other~~, CZO investigators routinely write op-eds and produce video ~~that are distributed~~ for distribution to media audiences and ~~teach~~ use in pre-college classrooms. For example, the Southern Sierra CZO is a contributor to the *Sustainable California* web TV channel that was launched with other collaborators. ~~The~~CZOs and the national CZO office ~~and other CZO have an active presence and following in~~ are active in ~~the~~ social media.

Eighth, CZOs act as *incubators that grow innovative teaching and mentor junior scientists* who ~~easily~~ readily work across multiple disciplines. As shown in Table 1, 39 post-doctoral scholars worked at CZOs in 2015 along with 106 undergraduate and 186 graduate students. As more and more institutions in the United States have advertised positions that mention critical zone science, these CZO students have moved easily into university department faculties where they are changing the research and education environment. Likewise, the recently completed InTeGrate project, *Introduction to Critical Zone Science*, is a one-semester undergraduate curriculum with lecture slides, online resources, and data drawn from the CZOs. This innovative new course uses the CZ as a unifying approach to teach complex Earth and environmental sciences (White et al., 2017). Many other teaching and training workshops have also been presented by the CZOs. For example, a Modeling Institute was presented in 2016 on the *Dhara* model (Le and Kumar, 2017, Woo and Kumar, 2017) and a training workshop was presented on the Role of Runoff and Erosion on Soil Carbon Stocks: From Soilscapes to Landscapes in collaboration with CUAHSI.

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Ninth, CZOs act as *impetus for discoveries and emergent hypotheses* that can only result from systematic and multi-disciplinary observations across multiple ~~or within specific~~ CZ environments. ~~Some~~ Some of these hypotheses are disciplinary while others ~~are~~ cross~~-disciplinary~~disciplines. A full elucidation of ~~these~~ hypotheses is beyond the scope of this paper~~; indeed, only~~ and only a subset are ~~of these are~~ shown in Table 4. M~~ while m~~any have been published ~~elsewhere~~ in collaborative papers (Rempe and Dietrich, 2014; Riebe et al., 2016; Li et al., 2017; Pelletier et al., 2017; Yan et al., 2017; Brantley et al., 2017, in press). Here we summarize three ~~of the most~~ multi-disciplinary ~~of the~~ discoveries that ~~. As it happens, all three~~ have large implications for the prediction of flowpaths relevant to the largest supply of accessible and drinkable water available to humans -- water contained in rock and regolith (Fetter, 2001; Banks et al., 2009). These ~~three~~ discoveries have been made both by non-CZO scientists and

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scientists within a CZO. F~~or example~~irst, one geophysics group outside of a ~~specific~~ CZO discovered a distinct geometry at depth that is consistent with the influence of regional tectonic stress fields on patterns of fractures and weathering ~~through~~ under hillslopes ~~at CZOs and other locations~~ (St. Clair et al., 2015). ~~-~~The theoretical underpinning proposed for this so-called "bowtie-shaped" geometry has important implications for predicting flowpaths of water in regolith *a priori*. CZOs also discovered significant water storage that is seasonally available in the vadose zone of weathered bedrock ~~and that moves as preferential flow along fractures~~ (Bales et al., 2011; Salve et al., 2012). This "*rock moisture*", missing from land surface models, has ~~very~~ significant implications for ~~understanding and~~ predicting climate. ~~-~~Finally, CZO workers have ~~also~~ identified depth intervals in the subsurface in some sites that document mineralogical reactions and that roughly mimic the land surface topography albeit with lower relief (Brantley et al., 2013). Such ~~"~~reaction fronts~~"~~ ~~can~~ inform researchers about sub-surface flow paths (Brantley et al., 2017). All of these ideas are being tested at other settings around the world.

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6 CZO m~~Three e~~easurements and models~~mergent paradigms~~

As mentioned above, common measurements are being made (Table 2) and models are being used across sites (Table 3). The measurements target the "SWEGS" fluxes – solute, water, energy, gas, and sediments -- as they move through the CZ, as well as such features as the form and age of the landscape and ecosystems (Fig. 4). Some of the observations are more extensive than others: for example, hydrometeorolog~~ical~~y~~ data~~, soil moisture dynamics, and measurements of concentration and discharge in streams are the focus of on-going efforts at every CZO.

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The CZOs' datasets are maintained ~~publically~~publicly available (http://criticalzone.org/national/data/) and are intended to serve the research community beyond those involved in each CZO. The types of data commonly include sensor and sampler measurements showing the temporal response of different locations in the CZ to meteoric events, spatially-resolved geophysical and geochemical measurements of CZ structure, and LiDAR measurements of vegetation and bare earth topography, among others. ~~-~~The CZOs are coordinating to ensure that measurements are comparable across sites (i.e., the "common measurements" effort). Likewise, efforts are ongoing so that the posted datasets can be used easily by others to make cross-site comparisons and conduct cross-site studies.

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The duration of time for individual data sets varies across the network. Generally, the time-series datasets (sensor and sampler arrays, eddy covariance, hydrometeorology, vadose zone and saturated zone aqueous chemistry, etc.) have durations that are roughly equivalent to the age of the CZO sites, determined by the initiation of NSF funding. One caveat is that CZOs have often added new study locations that were not among the original set, affecting the ~~duration~~ time interval of data that ~~are~~is available at each location. ~~-~~In other cases, measurement series may have been terminated as new measurements were brought on line.

Three sites (SSCZO, BCCZO and SSHCZO) have been in operation since 2007, and so their longer-term observational datasets extend roughly over that duration. ~~-~~Three other sites (CJCZO, LQCZO and CRCZO) that began operating two years later have measurements dating to 2009. ~~Three~~ Four newer sites (IMLCZO, CHCZO, RCCZO and ERCZO) have datasets dating to 2013. ~~-~~One observatory (CRCZO) ceased functioning as a CZO in 20~~xx~~14. Therefore, at present, continuous time series datasets range in duration from ca. 4 to 10 years. In addition, however, several of the CZOs are located in sites that provide longer datasets through previous measurement programs (for example, the extremely long datasets available at the Reynolds Creek CZO). ~~-~~The nature of ~~question of duration of~~ dataset duration is thus somewhat complex, and varies depending upon data type and site, but the generalized intent is to enable assessment of inter-annual variation ~~on a~~over decad~~al time scale~~es. The datasets are starting to drive extrapolations from the individual study sites to regional and continental scales. The duration of datasets also depends upon the residence times and mixing times of the various measured entities (Fig. 4).

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To integrate the measurements at different sites and to extrapolate forward and backward in time requires ~~One means of extending process understanding beyond specific sites is through~~ process-based modeling. As the common observational data accumulate, CZOs have been both developing new models and pursuing data comparisons with established models (Table 3). ~~and the datasets are starting to drive extrapolations from the individual study sites to regional and continental scales.~~ Currently, ~~as Table 3 indicates,~~ the initial CZ modeling efforts may be characterized into four groups as discussed below (Table 3).

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The first includes the modification and coupling of existing codes~~modifications and adoption of existing models~~ to ~~couple~~link ~~aspects of~~ various CZ processes (e.g., land-atmosphere exchange, saturated-unsaturated zone hydrology~~ and~~, biogeochemistry, ecology, ~~and biogeochemistry,~~ etc.) that are typically segregated in distinct models, but whose coupling is being revealed through CZ science measurements. The second includes identifying and filling critical gaps or knowledge of new processes such as hyporheic exchange, weathering, etc. The third includes development of a new generation of models that takes advantage of emerging streams of high-resolution data such as airborne- and UAV (unmanned aerial vehicle)-based LiDAR and hyperspectral data. The fourth includes coupling between fast and slow processes across many time scales. Slow processes provide the template for the fast response variable, while the accumulative effect of the latter results in the evolution of the former. Both mathematical frameworks and data to support such modeling are still in their infancy.

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7 Emergent network-level concepts

A central challenge of CZ science is the need to generalize from the place-based studies at observatories to principles-based understanding across the network or across the globe. One way to do this (perhaps the only way) is with models. Dialogue is ongoing as to whether the critical

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Formatted: Font: (Default) Times New Roman zone community will be best served through a single modeling framework or a library of existing models that allows more targeted exploration. Place-based studies can demand very specific investigations that are highly tuned to the biogeomorphic setting of a specific location, but that provide little deeper understanding. In contrast, a model that is broadly applicable may simplify the representation of a given site so much that the model results in reduced accuracy of prediction. Therefore, both the advancement of critical zone science and critical zone modeling will likely progress in an intertwined manner.

One way to further the evolution from place-based to principles-based understanding is to drive development of fundamental understanding at a network level, rather than the level of a single observatory. In fact, since initiation of the CZO effort in 2007, t

~~As mentioned above, common measurements are being made at all the CZOs in the U.S. (Table 2). In general, these measurements target the "SWEGS" fluxes – solute, water, energy, gas, and sediments – as they move through the CZ, as well as such features as the form and age of the landscape. Some of the observations are more extensive than others: for example, hydrometeorological data, soil moisture dynamics, and measurements of concentration and discharge in streams are on-going at every CZO. As the common observational data accumulate, CZOs have been both developing new models and pursuing data comparisons with established models (Table 3). In the last several years, researchers have not only been integrating observations within a CZO but also integrating across multiple CZOs. At the highest level of cross-network synthesis, three~~hree general, overarching ~~paradigms~~ concepts have emerged ~~which we describe below~~at the network level. Each of these describes deeper process- and principles-based understanding as summarized below.

First, we have observed that differences in natural and anthropogenic inputs at Earth's surface translate into differences in water, regolith structure, minerals, and biotic activity at depth, and we are starting to detect how these deep properties also impact the biota, climate, and CZ services (e.g. Richter and Billings, 2015; Sullivan et al., 2016; Richardson and Kumar, 2017; Chorover et al., 2011) ~~(Richter and Billings, 2015)~~.

Second, we have observed how the deep surface of the Critical Zone varies across landscapes. Under hills, imaging has revealed locally consistent patterns of subsurface critical zone structure ~~of~~ that can relate depth, fracture density, porosity, and weathering (e.g. Befus et al., 2011; Brantley et al., 2013; Orlando et al., 2015; St. Clair et al., 2015).

Third, we now have mechanistic models that provide quantitative predictions of the spatial structure of the deep surface relative to the ground surface topography (e.g. Lebedeva and Brantley, 2013; Rempe and Dietrich, 2014; Rasmussen et al., 2015; Riebe et al., 2016). These three broad generalizations have been informed by up to ten years of work at multiple CZOs as well as work by the greater critical zone science community (Banwart et al., 2011).

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In addition to the emergence of these network-level science concepts,~~With this ongoing integration of paradigms across CZOs, scientists have also begun to discern~~ an important link has emerged between the CZ and the ~~evolving~~ concept~~ualization~~ of "ecosystem services". This concept emphasizes how biodiversity, ecological processes, and spatial patterns in the near-surface environment provide services to society (MEA, 2005). As discussed by CZO network scientists (Field et al., 2015; 2016), CZ science demonstrates the contribution of the deeper CZ to ecosystem "provisioning" and elucidates the longer time scales of CZ evolution, leading to the idea of “critical zone services”. Through this lens, services such as water quality regulation, soil development, and carbon stabilization are seen as tightly dependent on CZ function, evolution and architecture. The valuation of CZ services offers an~~d~~ approach for assessment of human impact that takes into consideration both the short- and long-time scale processes ((Richardson and Kumar 2017). Indeed, the CZ is the ideal context for integrating deep subsurface and long time-scale perspectives from geosciences into the otherwise bio-centric conceptualization of ecosystem services. Doing so remains an emphasis of CZO network activities.

~~7~~ 8 Strengths and weaknesses of the current CZO network

The current CZO network as constituted in the U.S. and abroad has many strengths. Students are trained to cross disciplines within their ~~graduate~~ work, and they graduate with convergent expertise in the new field of CZ science. CZ science~~, which~~ is harmonizing ~~developing its own~~ vocabulary and conceptual understanding across disciplines, and is setting a research agenda~~,~~ and an integrated approach. Postdoctoral scholars ~~are educated~~learn from ~~with~~ observatory personnel that derive from many disciplines. Such scientists now ~~are able to~~ communicate as effectively~~, for example, on~~ about sapflow in trees as about ~~on~~ seasonal variations in groundwater flow~~, as the two are increasingly recognized as interdependent~~. Collaborations are constantly developing and allowing scientists to see problems ~~in new ways, and accepting new and~~ with different perspectives. Ideas are growing across the network about regolith formation (Riebe et al., 2016), snow hydrology (Harpold et al., 2014; Tennant et al., 2017), microbial diversity (Fierer et al., 2003), trees (Brantley et al., 2017, in press), ~~critical transitions (Kumar et al., 2017, in review),~~ and many other topics. We have produced ~~an~~ enormous datasets (http://criticalzone.org/national/data/datasets/). We no longer treat parts of the CZ as ~~mere~~isolated components or black boxes: instead, we incorporate more specificity and understanding when we describe the integrated system. We are finding innovative ways to communicate the CZ concept to the public. We have stimulated and promoted development of CZOs worldwide.

Although there have been many successes, we ~~have~~ also observe~~d~~ ~~several~~ weaknesses ~~in the approach as it is constituted today~~. Since each observatory is individually funded based on the merits of its targeted science ~~and management~~, there is ~~an obvious~~ competition ~~within each CZO~~ for allocation of resources ~~in addressing~~to address common ~~(network-wide)~~ measurements versus site-specific ~~measurements~~activities. This ~~competition for time and resources leads to~~

results in a less-than-optimal ~~approach to finding~~ identification of emergent network-scale outcomes ~~as opposed to individual, site-based outcomes~~. Of course, individual site-specific outcomes can have implications and impacts that are just as important as network-scale outcomes. Thus ~~and~~ we need to find mechanisms to foster all such approaches while acknowledging limitations in resources. Further, given how new CZ science is, ~~we are just~~insights are only just beginning to ~~articulate~~ emerge ~~transformative ideas~~ that cut across multiple disciplines. We still have occasional difficulty communicating these ideas ~~discoveries~~ in a simple fashion ~~on a transparent and inviting website~~. One specific example of a need for cross-disciplinary ideas and communication arises from the fact that the CZO network in the U.S. never emphasized social science. Thus, hypotheses have yet to emerge that target social science aspects of the CZ. Another challenge, and perhaps our biggest, ~~Perhaps one of our biggest challenges~~ is maintaining the integrity of an inter-disciplinary suite of measurements in a common database and managing site data (Fig. 4) in ways that invite other researchers to find and use the datasets ~~and use the field sites~~ (Hinckley et al., 2016). The need for better data management is especially important given the many new data-driven approaches that are arising within environmental science (Bui, 2016).

Th~~ese~~ese considerations in the context of the overview in this paper lead to a basic question: *~~what is the best way~~how might we design the best mechanism to advance CZ science?* ~~From review~~ W~~w~~e point to four specific challenges, posed here as questions, ~~going forward~~ that loom large in designing the future network. First, what is the best approach ~~for generalizing and scaling place-based studies to principles-based understanding through coordinated team effort~~to developing broadly-applicable principles from observatory-based investigations? Second, how do we link appropriately with other programs in the U.S. and worldwide to develop a set of representative sites across the large number of possible environmental gradients to advance a broad understanding of CZ science? Third, ~~how should we balance the roles of CZOs in providing infrastructure for monitoring while always~~ also ~~supporting hypothesis driven science~~how should we balance the roles of CZOs in developing long-term observational records versus shifting measurement strategies to advance and test new hypotheses? Fourth, what funding and management models would enable increased ~~and broader~~ involvement of ~~the broader community of~~ CZ scientists who are not yet part of ~~a~~ core CZO teams? These four issues are addressed in the next section where we propose a new model for the future of the network.

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~~8~~ 9 The future network

~~Different approaches~~ Mechanisms that have been successful in stimulating deeper understanding of ~~investigating aspects of~~ the environment were described above. These strategies can be summarized as i) small investigator ~~grants~~ projects targeting parts of the CZ, ii) campaign-style multi-investigator ~~grants~~ projects targeting multiple sites, iii) ~~modelling~~ center-based efforts, and iv) observatories. Looking into the future, all are needed.

For example, individual grants (example (i) from above) can ~~support~~ test~~ing of~~ sharply focused hypotheses that may lead to important discoveries about individual ~~elements or specific processes~~entities or processes~~ of the CZ~~. This kind of research, typically supported by a core grant from within a specific discipline (e.g., hydrology) sustains both the discipline and advances CZ science. The last decades of research has clearly shown that some advances come from single investigator research.

~~Approach~~ Mechanism (ii), campaign-style research, has the advantage of exploring CZ questions over a range of conditions (Larsen et al., 2015). Such campaigns ~~are more likely to~~ often focus on material properties ~~than~~ or process dynamics. C~~ and c~~ampaign-style research can focus many different one-time measurements, or measurements across a larger spatial scale, than CZOs can routinely accomplish. Campaigns typically incorporate small teams of researchers.

~~Modelling~~ Establishment of centers (approach iii) is ~~always~~ another important ~~as a~~ means to guide and test field data collection and to probe for deeper understanding by fostering communication and collaboration among many researchers. ~~-The~~However, the C~~ritical Zone Observatory~~ZO approach (iv) is the only approach that ~~tackles~~ forces diverse researchers to tackle fundamental questions at a single location ~~and~~while also ~~can also~~ ~~provideing~~ performing the nine important roles described above. ~~-~~In particular, only observatories ~~can~~ provide the long-term data and the diverse co-located observations from all disciplines that we need to understand the CZ. By working together with ~~modelling organizations~~centers, only place-based observatories can knit together disparate views by acting as ~~Meccas~~ gathering points for scientists from all disciplines with all their skills, instruments, and models.

However, because the CZ is highly heterogeneous, the network must be designed to promote the emergence of informative ideas that ~~can~~ supersedes~~ the heterogeneity of the CZ~~ this heterogeneity. In other words, CZOs ~~still need to perform more~~ must collaborative to engender ~~ly as a~~ network-level insights. Given this need, one approach may be for the community to identify a broad common-question for the future and then to design the future network to target this overall question. One proposed example for the next decade of CZO research is the following question of central importance:

> *How can we increase our understanding of surface and subsurface landscapes and fluxes as we face climate, land use, and other anthropogenic changes in the future?*

~~*How can we increase our understanding of surface and subsurface landscapes and fluxes as we face climate and other anthropogenic changes in the future?*~~

With such a question, the entire CZO network could ~~then~~ test sub-questions and sub–hypotheses together, but with experiments at different sites with different characteristics.

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~~To~~ Even if the CZOs target ~~address~~ this question together, some adjustments to the current topology of the CZO network should be evaluated and updated so as ~~,~~ to ~~continue performing the nine observatory roles listed above, orand to perform emerging roles~~promote the emergence of network-level ideas. Indeed, many other topologies can be imagined (Fig. ~~4~~5). ~~Going back as early as the 1960s (Leopold, 1962), many~~Many scientists have similarly considered aspects of what is needed for environmental networks (Leopold, 1962). For example, one topology might be to choose new observatories to fill in gaps among the current nine CZOs, as shown schematically in the diagram. Another model might be to continue the current nine CZOs as the future network in order to sustain both their unique observational records and the theoretical advances these advances enable. Another model might be to choose nine (or some other optimized number) completely new CZOs, i.e., treating the country as a blank slate. Another model might be to complete a careful analysis of the current CZOs in the context of Long Term Ecological Research (LTER) sites and Long Term Agricultural Research (LTAR) sites and then to extend the network appropriately~~ (see Richter et al., submitted)~~. NEON should also be part of this leveraging, as it becomes operational nationwide. A fifth model might be to establish ~~one~~ various “hub” locations and then choose smaller sites along environmental gradients extending out from the hub. Finally, many CZOs might be funded for research along with smaller satellite sites that extend from the central CZO.

In thinking about the future network topology, we emphasize the need to find solutions to the four problems~~,~~ stated as questions at the end of the last section: 1) the need to advance principles-based understanding from observatories; 2) the need to coordinate with other US programs and CZOs world-wide to sample a wide range of CZ conditions; 3) the need for balance between measurements for hypothesis-testing and common, core measurements as network infrastructure; and 4) the desire to incorporate an even broader community of researchers into the CZO program.

~~1) the need to generalize from place-based to principles-based understanding; 2) the inadequacy of nine observatories in elucidating the highly heterogeneous and variable CZ; 3) the need for balance between measurements for hypothesis-testing and common, core measurements as network infrastructure; and 4) the need to incorporate the broader community of researchers into the CZO program.~~

The best ~~way~~ topology to address these issues ~~appears to be~~ is ~~to~~ a design ~~something~~ like the hub-and-spoke model but with multiple hubs and a high degree of scientific coordination with the other networks noted above. In addition, instead of spokes, i.e., lines of satellite sites that extend geographically out from the hub, we prefer to call these “campaigns”, noting that in some cases these satellites might indeed be spokes, but in other cases they might be located in vastly disparate locations. This model would ~~promote~~ answer the need for long-term measurements (at carefully chosen hubs), the need for short-term targeted measurements at specific locations both within the U.S.A. and abroad (carefully chosen campaign sites), and ~~involve~~ the need for new mechanisms to engage ~~many new~~more investigators (funding to bring in scientists from outside the hub network)~~ as well~~. This long-term hub and short-term campaign emphasis has been

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promoted in the literature by researchers both inside and outside the current CZO funding framework (Banwart et al., 2012; Larsen et al., 2015). Fundamentally, the argument for the hub and campaign approach is that the two methods benefit from each other~~:~~. Specifically, the hub provides the unique opportunity to dig deep into understanding mechanisms and process dynamics~~.~~, whereas ~~T~~the campaign approach provides an opportunity to test the generality of specific findings, ideas, or theories across some relevant gradient, ~~of controls~~ e.g., in climate, land use, or ~~lithology~~tectonic activity while bringing in outside researchers.

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Specifically, we propose a “hubs-and-campaign” network that would consist of several (or all) of the CZOs as hubs that would provide the infrastructure for common measurements – and would be stimuli for ephemeral campaigns ~~that would be~~ funded for shorter ~~time~~ periods with more constrained purposes that incorporate non-CZO personnel. The hubs would perform all nine of the CZO roles listed above and would receive stable funding. In contrast, the campaigns would be funded in efforts for shorter time periods to test specific hypotheses or ideas. In this way, the network would be able to change appropriately with time and cover more environments, would provide both infrastructure and hypothesis testing, and could be nimble and inviting for more groups to participate.

I~~n this regard, i~~t makes sense ~~if~~for the hubs ~~were~~to be located in settings of broad interest from a scientific and societal point of view. For example, an urban CZO could be considered. Alternately (or in addition), the hubs could be located to test specific hypotheses about critical zone structure and controls across gradients of attributes such as ~~. Such gradients could include~~ climate or ~~lithology~~ tectonic activity or disturbance. Hubs ~~might be~~, chosen for their strategic and scientific importance~~.~~, ~~Hubs~~ would presumably also be chosen in recognition of the needs of human resources for education and outreach, and ~~for~~ of the need for both applied and curiosity-driven science. The potential use of hubs as attractors for students and scientists and platforms for increasing diversity in the Earth and environmental sciences would need to be stressed.

~~9~~ 10 Conclusions

We now recognize the critical zone as an entity composed of ~~very intriguing~~ co-evolving systems that create ~~a~~ the ~~remarkable~~ structured dynamic skin of the Earth. We are seeing the first maps of this structure as they emerge and we are discovering how the structure influences water resources and hydrologic processes, vegetation, ecosystems, erosion, biogeochemical processes, and even regional climate. Surface and deep processes are connected. ~~The~~A first set of testable models has ~~been proposed~~emerged and now points to specific measurement programs. But this is only the beginning. While progress has been made, the central questions remain: what controls the critical zone properties and processes, how does the critical zone~~s~~ respond to climate and land use change, and how can we use our advancing understanding to benefit societal needs?

These fundamental questions will require a sustained research commitment. The critical zone is a frontier area of science where only the first observations have been obtained. New methods, instrumentation, and theory are needed to ~~lay a foundation for~~continue to grow ~~-~~convergent understanding.

~~Here we suggest~~Future research in critical zone science ~~in future research may~~ will be best advanced through a combination of distributed long-term observatories strongly coupled with focused, campaign-style ~~focused~~ investigations. –These ~~field~~ campaigns would target new sites that might radiate from the central hub observatory to test specific hypotheses and theories across controlling gradients. The observatories would focus on the necessary long-term monitoring to reveal mechanisms and dynamics. The field campaigns would collect data over shorter periods.

The decision by the US National Science Foundation to support a network of Critical Zone Observatories since 2007 has laid the foundation ~~of~~ for a new discipline of critical zone science that has driven the convergence of individual scientific disciplines ~~since 2007~~. Former graduate students supported at the CZOs are now taking up faculty posts and rapidly introducing new courses that span the many disciplines needed to reveal critical zone workings. ~~Another~~ The next generation is in the making. –Findings from the CZOs are being absorbed by agencies and put to practice. The power of the critical zone concept has spread across the globe and stimulated the building of numerous critical zone observatories. –We are seeing just the beginning and it is time for the next chapter.

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Table 1. Metrics enumerating the U.S. CZO experiment

CZOs in the United States	9
CZOs worldwide	45*
Countries with interdisciplinary field observatories hosting CZ science**	25
Papers citing critical zone in keyword WOS as of 2017#	926
Papers listing critical zone in title in WOS as of 2017	242
Post-doctoral students educated at CZOs in 2015	39
Graduate students educated at CZOs in 2015	186
Undergraduate students educated at CZOs in 2015	106

*Includes Germany (TERENO), France (RBV/CRITEX), UK, and China

**Giardano and Houser (2015)

#Papers returned through searching Web of Science (WOS) as of 05/28/2017 that include “critical zone” in title or key word or abstract etc. (not including abstracts for meetings)

Table 2. Common measurements made at the CZO network in the U.S.A.

Critical Zone Observatory – Measurement Type	Boulder Creek	Cal-houn	Catalina-Jemez	Eel River	Intensively Managed Landscapes	Luquillo	Reynolds Creek	Susque~~hanna~~ Shale Hills	S. Sierra
Land-Atmosphere Exchange									
LIDAR	X	X	X	X	X	X	Y,Z	X	X,Y
Eddy flux	Y	Z	X		X,Y,Z		Y	X	X,Y,Z
Wind speed and direction	X	Z	X	X	X,Y	Y	Y	X	X
Precipitation and throughfall	X	X,Z	X	X	X,Y	Y	Y	X	X,Y
Wet deposition and bulk deposition	X	Z	X		Y	Y	Y	x	X,Y
Snowpack distribution and duration	X		X						X
Vegetation and Microbiota									
Structure and function above and below biomass	X	X	X	X	X	Y	Y,Z	X	X,Y
Microbial composition ~~above and below ground~~	X	X	X	X	X	Y	X	x	X
ET-species composition and structure relationships	Y	Z	X	Y	Y		Y,Z	X	X
Soil (Vadose Zone)									
Solid - elemental composition and mineralogy	X	X	X	X	X	X	Z	X	X,Y
Solid - texture and physical characterization	X	X	X	X	X	X	Z	X	X,Y
Solid – organic matter content	X	X	X	X	X	X	Z	X	X
Solid – radiogenic isotope composition	X	X	X		X	X		X	X,Z
Fluid – soil moisture (sensors)	X	X	X	X	X	X	Y,Z	X	X
Fluid – soil temperature (sensors)	X	X	X	X	X	X	Y,Z	X	X
Fluid – soil solution chemistry (samplers)	X	Z	X		X	X		X	X,Y
Fluid – soil gas chemistry (samplers/sensors)		X	X	X		X,Y	Z	X	X
Saprolite and Bedrock (Saturated Zone)									
Solid – petrology and mineralogy	X	X	X	X	Y	X	Z	X	X,Z
Solid – elemental composition and OM content	X	X	X	X	X	X	Z	X	X,Z
Solid – texture, physical/architectural constraints	X	X	X	X	X	X	Z	X	X
Fluid – potentiometric head, temperature (sensors)	X	X	X	X	X	X	Y	X	X
Fluid – groundwater chemistry (samplers/sensors)	X	X	X	X	X	X	Y	X	X
Fluid – saprolite/weathered bedrock gas chemistry		X	Z	X				x	
Geophysical surveys – depth to bedrock	X	X	X		X	X		X	X
Surface Water									
Instantaneous discharge	X	X	X	X	X,Y	X,Y,Z	Y	X	X,Y
Stable isotopes of water	X	X	X		X	X		X	X
Stream water chemistry (samplers/sensors)	X	X	X	X	X	X,Y,Z	Z	X	X,Y
Sediments (samplers/sensors)	X	X	X	X	X	X,Y,Z	Y,Z	X	Y,X
Extent of wetted channel				X					Y,X
Aquatic biota (invertebrates, fish, etc.)				X		Y			Y
Age or rate constraints									
Cosmogenic radionuclides	X	X	X			X		x	X
**C ages	X	X	X			X		x	
Optical Stimulated Luminescence ages	X								

x: instrumentation in place or sampling is occurring, owned and operated by the CZO; y indicates instrumentation is currently in place, owned and operated by a partner of the CZO; z indicates that it is planned to be installed or implemented in the future by the CZO

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Table 3: Models used by the U.S. CZOs (observatory abbreviations in Fig. 2)

Model name	**Systems modeled**	**~~Future~~ Possible X-CZO appli-cation?**	**CZOs using model**
PIHM	Hydrology	~~Possible~~x	CR, SH, CL
Flux-PIHM	Hydrology, land/atmosphere	~~Possible~~x	SH
tRIBS	Hydrology		LQ, CL
hsB-SM	Hydrology		CJ
VS2D	Unsaturated hydrology		BC
Dhara	Near surface critical zone	~~Possible~~x	IML, SH
Optimal sensing	Soil moisture		CL
Hydropedo Toolbox ~~(Matlab)~~	Soil moisture		SH
OTIS	Streambed hydrologic exchange		SH
Alpine glaciers 1&2d	Ice motion		BC
Fluid exchange ~~model~~	Estuary fluid flux		CR
PHREEQC	Aqueous geochemistry		LQ
WITCH	Weathering	~~Possible~~x	SH, CL
ROMS	Ocean		EL
WRF	Weather forecasting		EL, RC
ISNOBAL	Snowcover mass		RC, SS
SHAW	Heat and Water fluxes		RC
CHILD	Erosion, sediment transport, surface evolution	~~Possible~~x	BC, CL
SOrCERO	Erosion and deposition		CL
Digital glacier bed	Elevation of glacier bed		BC
Gully Erosion Profiler	Channel profile evolution		BC
Hillslope Trajectory	Erosion		BC
Range and Basin	Mountain evolution		BC
Landlab	General 2d models		BC
FEMDOC-2D	Hillslope DOC transport		CR
IDOCM_1D	Heat and DOC in soils		CR
CENTURY	Soil carbon		LQ
CN reforest dynamics	Tree/soil C and N		CL
BIOME BGC	Carbon		SH, RC
Plant-soil feedback	Plant-soil, soil production		CL
Root deformation	Soil deformation from roots		BC
GASH	ET and throughfall		LQ
NPZD	Ecosystem		EL
PIHMSed	~~Hydrology~~Water/~~,~~ sediment transport, uplift, weathering	~~Possible~~x	SH
PIHM-DOC	Hydrology, dissolved organic carbon		CR, SH
TIMS	Hydrology~~, ~~/microbi~~al,~~o/~~ ~~geochem~~ical,~~/ geomorph~~, ~~/ecology	~~Possible~~x	CJ
RHESSys	Hydrology, ecology	~~Possible~~x	SS

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AWESOM	Atmosphere/~~, Watershed~~watershed/~~,~~ ~~Ecology~~ecology/~~, Stream~~ stream~~and~~ /~~Ocean~~ ocean ~~Model~~	~~Possible~~x	EL
tRIBS-ECO	Hydrology, erosion, soil C		CL
WEPP/CENTURY-WEPP/WEPP-Rill1D(3ST1D)	Soil erosion, biogeochemistry	x	IML
OpenFOAM/BioChemFOAM	Riverine transport	x	IML
CRUNCH	Reactive transport	x	SH, IML, EL
Delft3D	Surface/subsurface transport	x	EL
Nays2D	Flood	x	IML

~~WEPP/CENTURY-WEPP/WEPP-Rill1D(3ST1D) Soil erosion, biogeochemistry Possible IML~~

~~OpenFOAM/BioChemFOAM Riverine transport Possible IML~~

~~CRUNCH Reactive Transport Possible SH/IML/EL~~

~~Delft3D Surface/sub-surface transport Possible EL~~

~~Nays2D Flood Possible IML~~

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Table 4. A few emergent hypotheses from the CZO network

1) CZ architecture controls hydrologic and geochemical processes that drive concentration-discharge relationships in rivers.
2) The depth to fresh bedrock across uplands landscapes may be predictable from models that account for regional stress fields, advancing chemical reaction fronts, drainage of the fresh bedrock, and/or fracturing from freeze-thaw.
3) Aspect differences can be used to reveal the mechanisms and effects of climate on the CZ.
4) The deep microbial community is linked to overlying vegetation: microbial community is distinctly different under agriculture fields, brush, grassland, perennial forest and deciduous forest.
5) The deep microbial community is linked to lithology: the microbial community is distinctly different on granite, basalt, shale, and sandstone.
6) The deep architecture of the Critical Zone controls water availability to plants and microbial communities, which in turn influence regional climates.
7) Subsurface reaction fronts may ~~sometimes~~ often be used to map flow paths in the subsurface.
8) Human impact in intensively managed landscapes has resulted in a critical transition that has changed the landscape from primarily a transformation-dominated system characterized by long residence times of water, carbon, and nutrients, to a transport-dominated system characterized by fast movement of water, sediment, carbon, and nutrients through the landscape into receiving water bodies.

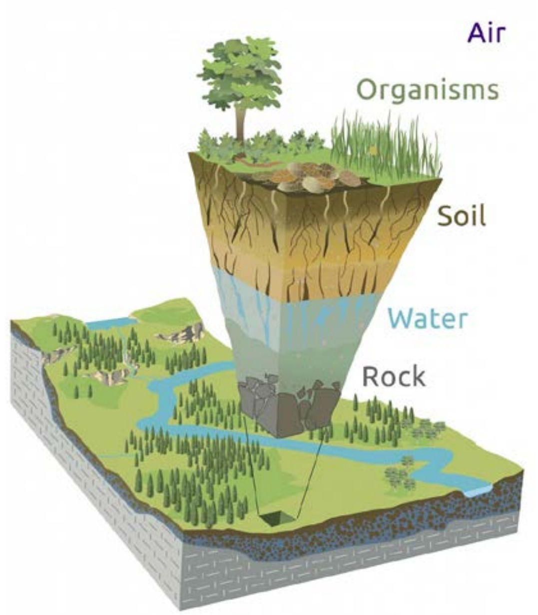

Figure 1. Understanding the critical zone requires harnessing insight from many disciplines on processes and fluxes from the top of the vegetation canopy down into groundwater~~,~~ at all spatial scales across timescales from milliseconds to millennia. Figure reproduced from ~~Anderson~~ Chorover et al. (200~~4~~7), ~~after an original drawing~~ artwork by R. Kindlimann.~~,~~

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Figure 2. The current network of ~~9~~ nine Critical Zone Observatories funded in the United States to investigate all aspects of the critical zone. Abbrevations used in Table 2: Eel River (ER), Southern Sierra (SS), Jemez Catalina (JC), Boulder Creek (BC), Reynolds Creek (RC), Intensively Managed Landscapes (IML), Susquehanna Shale Hills (SH), Calhoun (CL), Luquillo (L).

Figure 3. Location map of the 45 CZO locations in the U.S., Germany (TERENO), France (RBV/CRITEX), UK, and China that have been registered on Site Seeker (http://www.czen.org/site_seeker). The sites outside of Europe that are not in China are all operated by the French RBV/CRITEX program.

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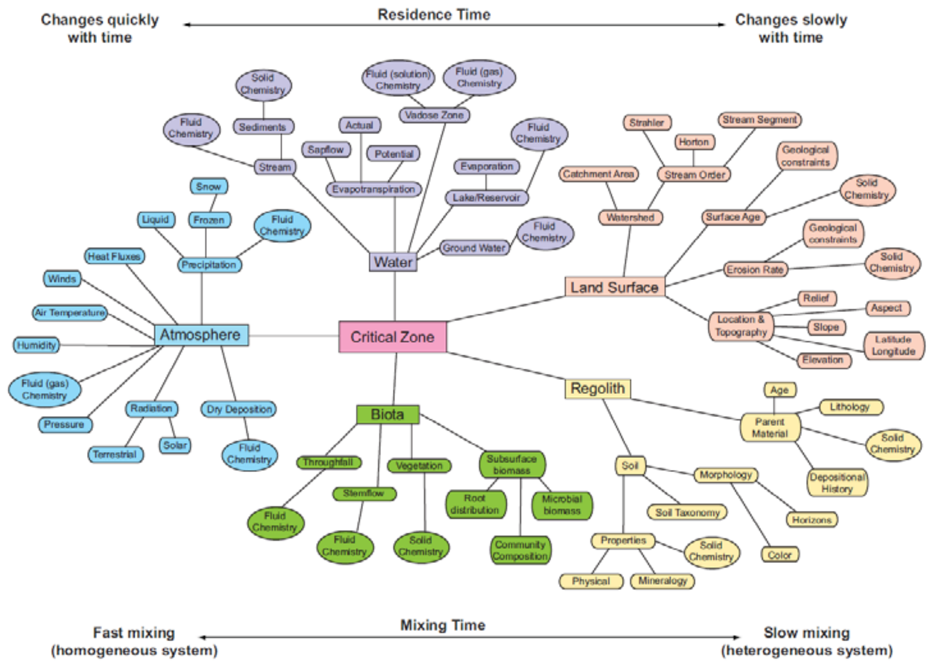

Figure 4. A schematic diagram showing some of the major entities that can be measured as part of the critical zone. The colors code entries related to the atmosphere (aqua), water (indigo), land surface features (beige), regolith (yellow), and biota (green). As shown by arrows, the entities are organized on the diagram from short to long residence times (left to right respectively), and these correlate with generally fast to slow mixing times respectively. Reproduced with permission from Niu et al. (2014).

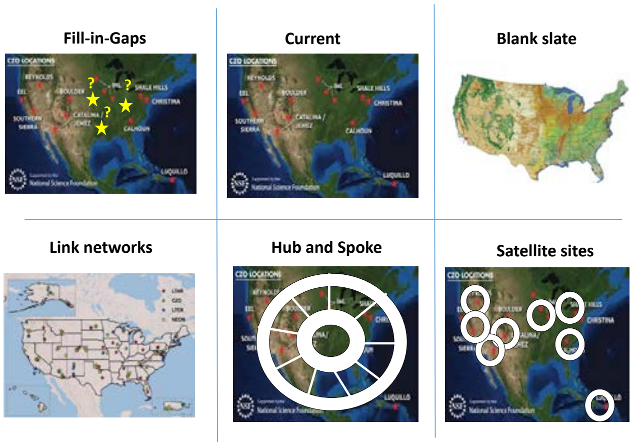

Figure ~~4~~5. ~~Possible c~~Conformations of a future CZO network discussed in the text. . The most effective topology is likely to be a combination of the observatory framework with smaller campaign-style science as discussed in the text, i.e., a “hubs-and-campaign” strategy.

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