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

Susan L. Brantley, Earth and Environmental Systems Institute, Department of Geosciences, The Pennsylvania State University, Univ. Park, PA 16802

William H. McDowell, Department of Natural Resources and the Environment, University of New Hampshire, Durham, NH, 03824

William E. Dietrich, Department of Earth and Planetary Science, UC Berkeley, CA 94720

Timothy S. White, Earth and Environmental Systems Institute, Department of Geosciences, The Pennsylvania State University, Univ. Park, PA 16802

Praveen Kumar, Department of Civil and Environmental Engineering, and Department of Atmospheric Science, University of Illinois, Urbana, Illinois 61801

Suzanne P. Anderson, Department of Geography, Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, CO 80309-0450

Jon Chorover, Department of Soil, Water and Environmental Science, University of Arizona, Tucson, AZ 85750

Kathleen Ann Lohse, Department of Biological Sciences, Idaho State University, Pocatello, ID 83209

Roger C. Bales, Sierra Nevada Research Institute and School of Engineering, University of California, Merced 94530

Daniel deB. Richter, Nicholas School of the Environment, Duke University, Durham, North Carolina 27708

Gordon Grant, Pacific Northwest Research Station, USDA Forest Service, Corvallis, OR 97331

Jérôme Gaillardet, Institut de Physique du Globe de Paris, Sorbonne Paris Cité, CNRS, Paris

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

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

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59

## 60 1 Introduction

61 Humans live at Earth's surface – a surface that changes at timescales ranging from  
62 milliseconds to millions of years. Understanding how to sustain a growing human population on  
63 this changing substrate while simultaneously sustaining diverse ecosystems is a grand challenge  
64 for scientists and decision makers (Millennium Ecosystem Assessment Board, 2005; Easterling,  
65 2007). In recognition of the critical nature of Earth's surface, the United States (U.S.) National  
66 Research Council defined the zone from the upper vegetative canopy through ground water as  
67 the “critical zone” and identified study of this “CZ” as one of the *Basic Research Opportunities*  
68 *in the Earth Sciences* (U.S. National Research Council Committee on Basic Research  
69 Opportunities in the Earth Sciences, 2001).

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

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

94 In the U.S., observatories to study the critical zone have been established by the National  
95 Science Foundation (NSF). The physical scope of these US CZOs varies, as some are defined by  
96 watershed boundaries, some by land use, others by the range of climate conditions, and still

97 others by contrasts in lithology or geomorphic history. The common elements are: 1) the focus  
98 on the entire above- and below-ground critical zone and its fluxes, 2) documentation of CZ  
99 structure, 3) mechanistic process studies, and 4) analysis of the history of the landscape that gave  
100 rise to its current structure. This last feature is a crucial aspect of CZOs that distinguishes them  
101 from previous studies that typically do not consider “deep time” (i.e., geologic time) and often  
102 fail to document the critical zone below the upper soil. Previous papers have described how  
103 researchers have grappled with the establishment of a measurement design at a specific CZO,  
104 with the overall data needs of CZOs, and with a modeling framework that might be used to  
105 tackle the complexity of timescales under consideration (Horsbaugh et al., 2008; Duffy et al.,  
106 2014; Niu et al., 2014; Brantley et al., 2016).

107 Over the last decade of study at individual CZOs, cross-CZO science has emerged and  
108 begun to unite the observatories into a CZO network with the capacity to test hypotheses across a  
109 larger parameter space than can be represented by any single CZO. As a result, network-level  
110 science has begun to emerge and provide opportunities that were not possible in the past. In this  
111 paper, we review the evolution of CZ science as an interdisciplinary “experiment.” We take  
112 stock of successes and weaknesses. The goal of the paper is to strategize about how to design a  
113 better CZO network to maximize future opportunities in CZ science at the levels of the  
114 individual observer, the observatory, the network and the broader Earth surface science  
115 community. Specifically, we address the broad question: what programs and infrastructure are  
116 needed by the community to understand the CZ of the future? The review is focused on activities  
117 and results of this endeavor to date in the U.S. We acknowledge the many other observatory  
118 networks around the world ([http://www.czen.org/site\\_seeker](http://www.czen.org/site_seeker)) and invite future papers on how  
119 those other networks are constituted and how the various observatory systems can work together.

120 One way to review the U.S. program to date is to summarize performance through  
121 quantitative metrics. As manifested today, the program funds nine CZOs situated across a range  
122 of landscapes (Fig. 2). In addition, interdisciplinary field observatories that host critical-zone  
123 science involve thousands of interdisciplinary investigators in more than 25 nations (Fig. 3)  
124 (Giardino and Houser, 2015). Other metrics further highlight how CZ science has energized  
125 people and approaches in the U.S. and abroad (Tables 1, 2, 3, 4). Indeed, the term “critical zone”  
126 has been used in 925 papers as of June 2017, in title, abstract, or keyword as recorded in Web of  
127 Science. The term has even entered the realm of geopolitics (Latour, 2014) and been defined in  
128 scientific dictionaries (White and Sharkey, 2016). This is remarkable given that critical-zone  
129 science as an idea only dates from 2001. Less quantifiable, however, is the impact of the idea of  
130 the CZ: for example, one country hosting one of the longest-functioning observatory networks in  
131 the world (France) is now specifically promoting communication among disciplines and sites.  
132 Researchers within that network have pointed to the internationally-emerging paradigm of the  
133 CZ as a driver for this new level of communication. Thus, quantitative metrics such as those in  
134 Table 1 do not fully illustrate the way CZ science has impacted science. In the rest of the paper  
135 we therefore discuss the evolution of observatories in environmental science, other mechanisms

136 for studying the CZ, the history of the CZO program, the nine roles of CZOs, and CZO  
137 measurements and models. We finish by discussing the strengths and weaknesses of the CZO  
138 approach to date and show how network-level understanding is starting to emerge. In the last  
139 section we consider an overarching question to drive future CZ science, and we propose a new  
140 topology for the CZO network.

## 141 **2 Historical context for environmental observatories and networks**

142 It is useful to place the CZ enterprise broadly into the context of environmental science.  
143 The differentiated scientific disciplines largely did not yet exist until the 1900s, and the earliest  
144 natural scientists therefore tended to be multi-disciplinary (e.g. Forbes, 1887; CFIR CSEPP,  
145 2005; Warkentin, 2006; Berner, 2012; Riebe et al., 2016). These researchers early on began to  
146 articulate the need for place-based, integrative science. This has led to a rich history of diverse,  
147 place-based, experimental, and long-term observation sites in the U.S. and world.

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

155 As human population and land use increased, researchers began to compare pristine sites  
156 to human-impacted sites, and began emphasizing the need for long-term measurements  
157 (Leopold, 1962). The U.S. Geological Survey thus developed a hydrologic benchmark network  
158 (HBN) of 57 basins (Cobb and Biesecker, 1971) to make long-term hydrologic measurements.  
159 The mandate of the HBN was expanded in 2011 to include long-term observations not only of  
160 stream flow and water quality but also of soil chemistry and aquatic ecology (McHale et al.,  
161 2014). Thirty-seven hydrologic benchmark watersheds are still maintained (Mast, 2013), but the  
162 original vision to also characterize vegetation and geology has remained unfulfilled.

163 The paired-watershed approach pioneered in Watson Wheel Gap, Colorado, was  
164 replicated much later in many other locations in the U.S., including Coweeta Hydrologic  
165 Laboratory (North Carolina), Hubbard Brook (New Hampshire), Reynolds Creek Experimental  
166 Watershed (Idaho), and the H.J. Andrews Experimental Forest (Oregon) among others. These  
167 pioneer sites, in turn, led to the establishment of over 70 Experimental Forests and Rangelands as  
168 sites that focus on fundamental and applied questions spanning hydrology, silviculture, soil  
169 science, and climate research (Lugo et al., 2006).

170 In the early 1980s, as academic scientists pointed out the difficulties of answering  
171 questions about long-term natural processes given the realities of short-term funding (Bormann  
172 and Likens, 1979; Callahan, 1984), the U.S. National Science Foundation Directorate of  
173 Biological Sciences created the Long-Term Ecological Research (LTER) program to carry out  
174 observation-based research across a network of sites that spanned the major biotic regions of

175 North America. These efforts were aided by early work of the U.S. Forest Service to understand  
176 watershed hydrology (Swank and Crossley, 1988). The LTER effort was initiated predominantly  
177 by ecosystem ecologists asking questions about organisms with long life cycles, including how  
178 they are maintained by natural water and nutrient fluxes in the face of acute environmental  
179 changes that are long-term as well as episodic (Dodds and al., 2012). Although not exclusively  
180 based on the study of watersheds as pioneered in the late 1960s (Bormann and Likens 1967),  
181 many LTERs follow a model that emphasizes the study of energy, water, and material flows  
182 through a watershed (Hynes 1975). As of 2017, the LTER network contains 28 LTERs and is  
183 beginning to emphasize the need to incorporate social science (LTER Network Office, 2011).

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

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

196 The most recent addition to the development of observatories in the U.S. is the National  
197 Ecological Observatory Network (NEON). NEON is a U.S.-wide, distributed observatory that  
198 aims to understand and forecast the impacts of climate change, land use, and invasive species on  
199 ecology and ecosystem fluxes by providing a research platform for investigator-initiated sensors,  
200 observations and experiments that can provide consistent, continental, long-term, multi-scaled  
201 data (Loescher et al., 2017). NEON has 84 sites across the U.S. Like LTER, NEON is a program  
202 funded by the Directorate of Biological Sciences at NSF to study ecological change (Golz et al.,  
203 2016).

204 As in the U.S., international observatory networks have also grown, many for  
205 substantially the same reasons that they grew in the U.S. – to study land use, water, and ecology.  
206 In at least one country (France), a network (OZCAR: Observatoires de la Zone Critique:  
207 applications et recherche) emphasizes individual disciplines at each observatory and provides as  
208 much as 50 years' worth of data to enable research in some sites. The long-term, place-based  
209 ecological research that was pioneered by the LTER network in the U.S.A. has also been adopted  
210 by the broader international community in the International LTER (ILTER) network (Vanderbilt  
211 and Gaiser, 2017). Today, the European Commission is promoting an approach to develop a  
212 European Research Infrastructure in the form of a network associating CZOs, LTERs and  
213 LTSEs. Here, LTSE stands for Long Term Socio-Ecological Research, i.e., a network that

214 also incorporates questions from social science. Indeed, many of the European countries  
215 maintain strong observatory infrastructures that are much more tightly linked with local  
216 stakeholders than observatories in the U.S. This may result from the lack of truly “natural”  
217 territories in Europe, given the long history of development on the continent but also the  
218 willingness to co-construct research questions with stakeholders to build a sustainable  
219 environmental future.

### 220 **3 Non-observatory approaches used to study the CZ**

221 Just as observatory science was beginning with the Watson Wheel Gap observatory in the  
222 early 1900s, scientists also began to focus on portions of the Earth system that could be  
223 understood in a reductionist sense (Riebe et al., 2016). Eventually, small-grant funding to single  
224 investigators or small teams became the dominant mechanism to fund research to explore  
225 questions about the CZ. This targeted approach further emphasized reductionism and served to  
226 grow the individual disciplines of geochemistry, geobiology, geomorphology, hydrology, soil  
227 science, ecology, meteorology, and others. Disciplinary growth in turn allowed relatively defined  
228 “monodisciplinary” paradigms to mature and led to the proliferation of disciplinary journals. For  
229 example, Web of Science currently indexes 225 journals in the fields of environmental sciences,  
230 184 in geosciences, and 150 in ecology, with some journals cross-reported in more than one  
231 category.

232 Through smaller funded projects, many different types of measurements were made.  
233 However, the measurements were completed at different sites and integration of observations  
234 into models was difficult to impossible. Advances in studying Earth’s surface tended to be  
235 uneven because different sites were targeted and coordination among disciplinary approaches  
236 was lacking. Such fragmentation accentuated the need for observatories. Other mechanisms were  
237 also needed, however, as questions about environmental impacts on human health grew in the  
238 U.S. throughout the 1970s (CFIR CSEPP, 2005). Funding agencies began seeking teams of  
239 researchers to pursue campaigns – concerted, multi-investigator, multi-year projects – targeting  
240 focused hypotheses about landforms, soils, water, biota, in addition to human health. Such  
241 campaigns culminated in global efforts such as the Millenium Ecosystems Assessment  
242 (Millenium Ecosystem Assessment Board, 2005) and the International Geosphere-Biosphere  
243 Program (IGBP). The latter initiative engaged 10,000 scientists from more than 20 disciplines  
244 and 80 countries (CFIR CSEPP, 2005; Millenium Ecosystem Assessment Board, 2005).

245 Eventually, another type of funding mechanism to study the CZ emerged in the U.S.  
246 alongside observatory, single-investigator, and campaign-style science. Specifically, centers of  
247 excellence were funded to draw together scientists into institutions to focus on specific problems  
248 or approaches. One impetus for this was the inauguration in 1987 of the NSF Science and  
249 Technology Center program. This effort eventually supported two centers of special relevance to  
250 critical zone research: SAHRA (Sustainability of Semi-Arid Hydrology and Riparian Areas) and

251 NCED (National Center for Earth-surface Dynamics). NCED (2002 to 2012) focused on  
252 developing a quantitative, predictive Earth-surface science by integrating geomorphology,  
253 ecology, hydrology, sedimentary geology, engineering, social sciences, and geochemistry by  
254 combining field, experiment, and computational approaches. NCED and its reincarnation as  
255 NCED2 after 2012 both emphasize predictive Earth-surface science. A similarly ambitious  
256 institution, the National Center for Ecological Analysis and Synthesis (NCEAS), was established  
257 in 1995 as the first national synthesis center for ecology. Neither of these centers focused on the  
258 CZ as one single entity.

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

#### 271 **4 The CZO program**

272 Even with this variety of funding mechanisms for Earth and environmental science, no  
273 concerted nationwide effort emerged to tackle questions and to train students to target the CZ as  
274 one entity, incorporating the deep geological underpinnings and long-timescale perspectives. As  
275 a result, the environmental science that developed often had to rely on statistical approaches to  
276 explain variability instead of developing more fundamental explanations based on underlying  
277 geological heterogeneity and its origins. Recognizing the need to emphasize the geological  
278 underpinnings of place-based science in the late 2000s, researchers within the water, soil,  
279 geochemistry, and geomorphology communities began articulating a need for integrated science  
280 across the entire zone from canopy to bedrock to incorporate the full significance of the  
281 underlying geology (Anderson, 2004; Brantley et al., 2006; Chorover et al., 2007; U.S.  
282 Committee on Integrated Observations for Hydrologic and Related Sciences, 2008; U.S. Steering  
283 Committee for Frontiers in Soil Science, 2009; U.S. National Research Council, 2010; Banwart  
284 et al., 2011; Committee on New Research Opportunities in the Earth Sciences at the National  
285 Science Foundation, 2012; White and Sharkey, 2016).

286 Eventually the need to study the CZ as one integrated entity resulted in the NSF program  
287 establishing the Critical Zone Observatory program in 2007 (White et al., 2015). In this initial



288 phase, three CZOs were funded (Anderson et al., 2008). Two years later, three more CZOs were  
289 funded. By 2013 this number had grown to nine observatories supported through a competitive  
290 selection process. In addition to the expansion of sites in 2013, a CZO National Office (NO) was  
291 established by NSF in 2014 through a competitive process, with the intent of providing the CZO  
292 Network with an administrative structure for furthering coordination (White et al., 2015). The  
293 number of CZOs has remained stable through 2017.

294 Inauguration of the CZO program implicitly defined the term “critical zone observatory”  
295 to be distinct within the long history of observatories in the US and abroad as an observatory that  
296 promotes study of the entire CZ as one entity. As implemented today, CZOs are sites or closely  
297 connected sets of sites with no required size or specified range of conditions. In fact, the  
298 physical scope of a CZO is set only by the fundamental questions driving the establishment of  
299 the observatory. A fundamental characteristic of a CZO is that it is able to operate over a long  
300 enough period to quantify controlling mechanisms thoroughly and to capture temporal trends that  
301 reveal how the critical zone operates. Two more characteristics of a CZO are that it is amenable  
302 to study by many disciplines and that it integrates understanding of long- and short-timescale  
303 phenomena. Finally, each CZO operates as an adaptive and agile hypothesis-testing machine,  
304 not simply a monitoring program. As CZOs developed in the U.S., they began to play nine  
305 important roles within the environmental scientific endeavor. These are described in the next  
306 section.

## 307 **5 The nine emergent roles of CZOs**

308 Here the nine important roles of an observatory are described with examples of scientific  
309 results from across the CZO network today.

310 First, CZOs act as *synthesizers of interdisciplinary research into convergent approaches*  
311 at one specific site that lead to novel understanding and ultimately result in more deeply-  
312 informed generalized and predictive understanding (Rasmussen et al., 2011a). In other words,  
313 observatories induce scientists from different disciplines to make measurements using different  
314 disciplinary approaches at the same location instead of making them at disparate sites, driving  
315 cross-disciplinary understanding in describing CZ function (Hynek et al., 2016; Sullivan et al.,  
316 2016; Yan et al., 2017; Chen et al., 2017 in press). At first, much of the synthesis crossed only  
317 two disciplines at a time: for example, several papers emphasized how geomorphological  
318 concepts related to erosion must be incorporated to understand chemical weathering, and vice  
319 versa (Rempe and Dietrich, 2014; Riebe et al., 2016). Likewise, researchers have related tree  
320 roots to water cycling (Vrettas and Fung, 2015). Now, researchers are targeting multi-disciplinary  
321 aspects of CZ entities. For example, at the Calhoun CZO, where the South Carolina landscape  
322 was severely eroded by cotton farming, logistic regression models treat market and policy  
323 conditions in the context of topographic characteristics (Coughlan et al. 2017). By fostering

324 measurements from all disciplines in centralized places, CZOs are discovering not only how to  
325 cross disciplines but how individual disciplines can converge.

326         Second, CZOs provide *stable platforms for long-term measurements* (Table 2). Some  
327 datasets synthesized by CZOs are now available for decades or several decades. For example, the  
328 Reynolds Creek CZO recently published 31 years of hourly data that are spatially distributed at  
329 10 m resolution for air temperature, humidity, and precipitation (Kormos et al., 2016) and a 10-  
330 year data set that spans the rain-snow transition (Enslin et al., 2016). Similarly, decreasing trends  
331 in water and energy influx in the Jemez CZO over the past 30 years were recently related to CZ  
332 structure (Zapata-Rios et al., 2016). Major changes in soil biogeochemistry have been  
333 documented by Calhoun CZO researchers over 50-years of reforestation in fields cultivated for  
334 cotton (Mobley et al., 2015). That CZO also spearheads an effort to recover archived data from  
335 three eroded watersheds that were farmed from the late 1940s to 1962 – as well as to re-  
336 instrument the catchments. Many other multi-year measurements common to all CZOs enable  
337 hypothesis-testing. For example, characterization of dissolved organic matter (DOM) measured  
338 with similar methodology across five CZOs revealed a strong role for CZ structure in setting the  
339 origin, composition and fate of DOM in streams (Miller et al., 2016). In another example, a  
340 coordinated effort emerged to measure and understand the relationships among solute  
341 concentrations and water discharge in streams (e.g. Kirchner, 2003; Godsey et al., 2009). A  
342 special issue on the topic (Chorover et al., 2017, in press) is pointing the way toward the use of  
343 knowledge of subsurface structure to explain concentration-discharge behavior *a priori*.

344         Third, CZOs act as *a stimulus and test-bed for modelling and prediction*. Modeling the  
345 CZ is a unique challenge in that models must address the coupling across time scales from  
346 seconds to millennia (Table 3). To tackle this challenge, CZOs are both adapting existing models  
347 and developing new models. For example, one CZO is developing a hierarchy of modules to  
348 describe processes that occur over seconds to millennia (Duffy et al., 2014). For long timescale  
349 processes, almost every CZO has proposed models of regolith formation, and many are  
350 summarized in a special issue (Riebe et al., 2016). At the shorter timescales, standard water or  
351 coupled land surface-air models have been tested and new modules developed (Table 3). To  
352 exploit high resolution data such as LiDAR and hyperspectral measurements, modelling efforts  
353 explore micro-topographic and vegetation controls on soil moisture (Le et al., 2015; Le and  
354 Kumar, 2017) as well as biogeochemical changes in agricultural landscapes (Woo and Kumar,  
355 2017). Researchers have likewise developed a energy-balance snowmelt model that is now being  
356 used with remotely sensed data for water supply forecasting (Painter et al., 2016). In other  
357 integrative efforts, researchers are modelling how hydraulic conductivity, root water uptake  
358 efficiency, and hydraulic redistribution by plants sustain evapotranspiration through dry seasons  
359 (Quijano et al., 2012; Quijano et al., 2013; Vrettas and Fung, 2015). Work at the Luquillo CZO  
360 has supported interpretations of the controls on bedload grain size and channel dimensions for  
361 rivers (Phillips and Jerolmack, 2016). Researchers at the Calhoun CZO are using distributive  
362 models to explore relationships between topographic variations and the landscape's capacity to  
363 serve as an atmospheric carbon source or sink (Dalyanis et al., 2015).

364

365 Fourth, CZOs act as *baselines to understand and teach about the impact of catastrophic*  
366 *events*. For example, two western CZOs in the U.S. have studied the impacts of wildfire on soil  
367 microbiota (Weber et al., 2014), sediment yields (Pelletier and Orem, 2014), snow accumulation  
368 (Harpold et al., 2014), and water quality (Murphy et al., 2012; Reale et al., 2015). Likewise,  
369 effects of the 2013 Colorado Front Range storm (Gochis et al., 2015) on debris flows (Anderson  
370 et al., 2015), soil moisture (Ebel et al., 2015), cosmogenic radionuclides (Foster and Anderson,  
371 2016), and concentration-discharge behavior (Rue et al., 2017) were studied at the Boulder Creek  
372 CZO. A flash flood within Boulder Creek CZO in 2016 instigated analysis of Horton overland  
373 flow in these landscapes (Klein et al., 2017). CZOs that experience catastrophic events use the  
374 baseline data captured before the event to place the impact into perspective. An additional  
375 attribute is that such natural disasters engender public interest in research: research on the 2013  
376 Colorado Front Range storm from the Boulder Creek CZO and wildfire research from three  
377 CZOs has been featured in radio, press, and public forums. The important role of observatories in  
378 recording catastrophic events was reinforced by Hurricanes Irma and Maria, which brought  
379 winds up to 250 km h<sup>-1</sup> and enormous rainfall to the island of Puerto Rico in September 2017.  
380 The Luquillo CZO quantified winds, rains, and stormflows and will document Maria's impacts to  
381 forest canopies, accelerated tree throw, and mass hillslope movements for many years to come.

382 Fifth, CZOs act as *the organizing design for systematic campaigns to investigate process-*  
383 *based mechanisms* across different types of CZ. One example of this is the initiative in which  
384 every CZO in the U.S. pursued geophysical measurements. Many papers have been published  
385 exemplifying this approach to map out the subsurface architecture (Befus et al., 2011; Holbrook  
386 et al., 2014; Orlando et al., 2015; Olyphant et al., 2016). Now, geophysicists travel among CZOs  
387 to image the subsurface with a battery of instruments to image the below-ground landscape (St.  
388 Clair et al. 2015). In another example, after the Boulder Creek CZO began emphasizing slope  
389 aspect as a useful natural experiment to examine controls on CZ architecture and function in  
390 2009, similar analyses at other CZOs led to highlighted linkages among aspect, water, biota,  
391 regolith structure, and episodic events (West et al., 2014; Ebel et al., 2015; Pelletier et al., 2017).  
392 Finally, a deep drilling project (“drill the ridge”) was proposed and then pursued at many CZOs,  
393 and these data in turn led to a special issue describing regolith formation (Riebe et al., 2016).  
394 Successful campaigns have also been mounted to investigate mountain snow and water balance  
395 (Harpold et al., 2014).

396 Sixth, CZOs act as *catalysts for the development of new techniques and instrumentation*  
397 which can then be tested globally. For example, at the Eel River CZO, a unique vadose zone  
398 monitoring system (VMS) has been installed consisting of holes drilled into a hill at 55° relative  
399 to the horizontal to monitor for temperature, pressure, and electrical conductivity. The VMS  
400 probes the generally inaccessible deep vadose zone to test reactive transport models  
401 incorporating gas and water chemistry (Druhan et al., 2017). At another CZO, experiments  
402 designed to improve management practices for erosion have elucidated controls on the  
403 concentration of carbon in eroded sediment and original soil (Papanicolaou et al., 2015). One

404 CZO is exploring weathering reactions through the use of neutron scattering (NS) to analyze  
405 pores as small as nanometers in rocks (Navarre-Sitchler et al., 2013). Water-balance  
406 instrumentation using robust wireless-sensor networks, developed at the Southern Sierra CZO  
407 (Kerkez et al., 2012), has been extended to the river-basin scale (Zhang et al., 2017), and is being  
408 deployed at other locations across the U.S. An approach developed to scale annual  
409 evapotranspiration measured at flux towers across the broader forested landscape of the Sierra  
410 Nevada (Goulden et al., 2012) is also being applied to flux-tower sites and forested areas across  
411 the western U.S.

412         Seventh, CZOs serve as *hubs for informing regional resource-management decisions, and*  
413 *for educating the public about societally relevant problems.* For example, measurements of  
414 evapotranspiration made at one CZO and scaled across the Sierras provide a basis for estimating  
415 sustainable forest densities today and into the future when the climate will be warmer and drier  
416 (Goulden and Bales, 2014). Research on water resources is routinely communicated to water  
417 managers in California and the intermountain west by the Southern Sierra CZO through  
418 briefings, workshops and data products. Results from Catalina-Jemez CZO studies of wildfire  
419 impacts on watershed-scale sediment transport are also being considered in the development of  
420 forest management strategies in two states. Research on snowpack and water resources by the  
421 Boulder Creek CZO has similarly been communicated in a series of workshops for water  
422 managers in Colorado, Utah and Wyoming in 2015. In other parts of the country, the Eel River  
423 CZO is documenting controls on the spread of cyanobacteria in the Eel River, and information is  
424 disseminated in biannual gatherings of students, agency members, native Americans, and  
425 practitioners. IMLCZO is developing a series of courses for crop advisors in the US agricultural  
426 Midwest. Finally, CZO investigators routinely write op-eds and produce video for distribution to  
427 media audiences and use in pre-college classrooms. For example, the Southern Sierra CZO is a  
428 contributor to the *Sustainable California* web TV channel that was launched with other  
429 collaborators. CZOs and the national CZO office are active in social media.

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

442 the Role of Runoff and Erosion on Soil Carbon Stocks: From Soilscales to Landscapes in  
443 collaboration with CUAHSI.

444 Ninth, CZOs act as *impetus for discoveries and emergent hypotheses* that can only result  
445 from systematic and multi-disciplinary observations across multiple CZ environments. Some of  
446 these hypotheses are disciplinary while others cross disciplines. A full elucidation of hypotheses  
447 is beyond the scope of this paper and only a subset are shown in Table 4. Many have been  
448 published in collaborative papers (Rempe and Dietrich, 2014; Riebe et al., 2016; Li et al., 2017;  
449 Pelletier et al., 2017; Yan et al., 2017; Brantley et al., 2017, in press). Here we summarize three  
450 multi-disciplinary discoveries that have large implications for the prediction of flowpaths  
451 relevant to the largest supply of accessible and drinkable water available to humans – water  
452 contained in rock and regolith (Fetter, 2001; Banks et al., 2009). These discoveries have been  
453 made both by non-CZO scientists and scientists within a CZO. First, one geophysics group  
454 outside of a CZO discovered a distinct geometry at depth that is consistent with the influence of  
455 regional tectonic stress fields on patterns of fractures and weathering under hillslopes (St. Clair  
456 et al., 2015). The theoretical underpinning proposed for this so-called “bowtie-shaped” geometry  
457 has important implications for predicting flowpaths of water in regolith *a priori*. CZOs also  
458 discovered significant water storage that is seasonally available in the vadose zone of weathered  
459 bedrock (Bales et al., 2011; Salve et al., 2012). This “*rock moisture*”, missing from land surface  
460 models, has significant implications for predicting climate. Finally, CZO workers have identified  
461 depth intervals in the subsurface in some sites that document mineralogical reactions and that  
462 roughly mimic the land surface topography albeit with lower relief (Brantley et al., 2013). Such  
463 reaction fronts inform researchers about sub-surface flow paths (Brantley et al., 2017). All of  
464 these ideas are being tested at other settings around the world.

## 465 **6 CZO measurements and models**

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

472 The CZOs’ datasets are maintained publicly available  
473 (<http://criticalzone.org/national/data/>) and are intended to serve the research community beyond  
474 those involved in each CZO. The types of data commonly include sensor and sampler  
475 measurements showing the temporal response of different locations in the CZ to meteoric events,  
476 spatially-resolved geophysical and geochemical measurements of CZ structure, and LiDAR  
477 measurements of vegetation and bare earth topography, among others. The CZOs are  
478 coordinating to ensure that measurements are comparable across sites (i.e., the “common

479 measurements” effort). Likewise, efforts are ongoing so that the posted datasets can be used  
480 easily by others to make cross-site comparisons and conduct cross-site studies.

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

488 Three sites (SSCZO, BCCZO and SSHCZO) have been in operation since 2007, and so  
489 their longer-term observational datasets extend roughly over that duration. Three other sites  
490 (CJCZO, LQCZO and CRCZO) that began operating two years later have measurements dating  
491 to 2009. Four newer sites (IMLCZO, CHCZO, RCCZO and ERCZO) have datasets dating to  
492 2013. One observatory (CRCZO) ceased functioning as a CZO in 2014. Therefore, at present,  
493 continuous time series datasets range in duration from ca. 4 to 10 years. In addition, however,  
494 several of the CZOs are located in sites that provide longer datasets through previous  
495 measurement programs (for example, the extremely long datasets available at the Reynolds  
496 Creek CZO). The nature of dataset duration is thus somewhat complex, and varies depending  
497 upon data type and site, but the generalized intent is to enable assessment of inter-annual  
498 variation over decades. The datasets are starting to drive extrapolations from the individual study  
499 sites to regional and continental scales. The duration of datasets also depends upon the residence  
500 times and mixing times of the various measured entities (Fig. 4). To integrate the measurements  
501 at different sites and to extrapolate forward and backward in time requires process-based  
502 modeling. As the common observational data accumulate, CZOs have been both developing new  
503 models and pursuing data comparisons with established models (Table 3). Currently, the initial  
504 CZ modeling efforts may be characterized into four groups as discussed below (Table 3).

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

## 516 **7 Emergent network-level concepts**

517 A central challenge of CZ science is the need to generalize from the place-based studies  
518 at observatories to principles-based understanding across the network or across the globe. One  
519 way to do this (perhaps the only way) is with models. Dialogue is ongoing as to whether the  
520 critical zone community will be best served through a single modeling framework or a library of  
521 existing models that allows more targeted exploration. Place-based studies can demand very  
522 specific investigations that are highly tuned to the biogeomorphic setting of a specific location,  
523 but that provide little deeper understanding. In contrast, a model that is broadly applicable may  
524 simplify the representation of a given site so much that the model results in reduced accuracy of  
525 prediction. Therefore, both the advancement of critical zone science and critical zone modeling  
526 will likely progress in an intertwined manner.

527 One way to further the evolution from place-based to principles-based understanding is to  
528 drive development of fundamental understanding at a network level, rather than the level of a  
529 single observatory. In fact, since initiation of the CZO effort in 2007, three general, overarching  
530 concepts have emerged at the network level. Each of these describes deeper process- and  
531 principles-based understanding as summarized below.

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

537 Second, we have observed how the deep surface of the Critical Zone varies across  
538 landscapes. Under hills, imaging has revealed locally consistent patterns of subsurface critical  
539 zone structure that can relate depth, fracture density, porosity, and weathering (e.g. Befus et al.,  
540 2011; Brantley et al., 2013; Orlando et al., 2015; St. Clair et al., 2015).

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

546 In addition to the emergence of these network-level science concepts, an important link  
547 has emerged between the CZ and the concept of "ecosystem services". This concept emphasizes  
548 how biodiversity, ecological processes, and spatial patterns in the near-surface environment  
549 provide services to society (MEA, 2005). As discussed by CZO network scientists (Field et al.,  
550 2015; 2016), CZ science demonstrates the contribution of the deeper CZ to ecosystem  
551 "provisioning" and elucidates the longer time scales of CZ evolution, leading to the idea of  
552 "critical zone services". Through this lens, services such as water quality regulation, soil  
553 development, and carbon stabilization are seen as tightly dependent on CZ function, evolution

554 and architecture. The valuation of CZ services offers an approach for assessment of human  
555 impact that takes into consideration both the short- and long-time scale processes ((Richardson  
556 and Kumar 2017). Indeed, the CZ is the ideal context for integrating deep subsurface and long  
557 time-scale perspectives from geosciences into the otherwise bio-centric conceptualization of  
558 ecosystem services. Doing so remains an emphasis of CZO network activities.

## 559 **8 Strengths and weaknesses of the current CZO network**

560 The current CZO network as constituted in the U.S. and abroad has many strengths.  
561 Students are trained to cross disciplines within their work, and they graduate with convergent  
562 expertise in the new field of CZ science. CZ science is harmonizing vocabulary and conceptual  
563 understanding across disciplines, and is setting a research agenda and an integrated approach.  
564 Postdoctoral scholars learn from observatory personnel that derive from many disciplines. Such  
565 scientists now communicate as effectively about sapflow in trees as about seasonal variations in  
566 groundwater flow. Collaborations are constantly developing and allowing scientists to see  
567 problems with different perspectives. Ideas are growing across the network about regolith  
568 formation (Riebe et al., 2016), snow hydrology (Harpold et al., 2014; Tennant et al., 2017),  
569 microbial diversity (Fierer et al., 2003), trees (Brantley et al., 2017, in press), and many other  
570 topics. We have produced enormous datasets (<http://criticalzone.org/national/data/datasets/>). We  
571 no longer treat parts of the CZ as isolated components or black boxes: instead, we incorporate  
572 more specificity and understanding when we describe the integrated system. We are finding  
573 innovative ways to communicate the CZ concept to the public. We have stimulated and promoted  
574 development of CZOs worldwide.

575 Although there have been many successes, we also observe weaknesses. Since each  
576 observatory is individually funded based on the merits of its targeted science, there is  
577 competition for allocation of resources to address common measurements versus site-specific  
578 activities. This results in a less-than-optimal identification of emergent network-scale outcomes.  
579 Of course, individual site-specific outcomes can have implications and impacts that are just as  
580 important as network-scale outcomes. Thus we need to find mechanisms to foster all such  
581 approaches while acknowledging limitations in resources. Further, given how new CZ science is,  
582 insights are only just beginning to emerge that cut across multiple disciplines. We still have  
583 occasional difficulty communicating these ideas in a simple fashion. One specific example of a  
584 need for cross-disciplinary ideas and communication arises from the fact that the CZO network  
585 in the U.S. never emphasized social science. Thus, hypotheses have yet to emerge that target  
586 social science aspects of the CZ. Another challenge, and perhaps our biggest, is maintaining the  
587 integrity of an inter-disciplinary suite of measurements in a common database and managing site  
588 data (Fig. 4) in ways that invite other researchers to find and use the datasets (Hinckley et al.,  
589 2016). The need for better data management is especially important given the many new data-  
590 driven approaches that are arising within environmental science (Bui, 2016).



591           These considerations in the context of the overview in this paper lead to a basic question:  
592 *how might we design the best mechanism to advance CZ science?* We point to four specific  
593 challenges, posed here as questions, that loom large in designing the future network. First, what  
594 is the best approach to developing broadly-applicable principles from observatory-based  
595 investigations? Second, how do we link appropriately with other programs in the U.S. and  
596 worldwide to develop a set of representative sites across the large number of possible  
597 environmental gradients to advance a broad understanding of CZ science? Third, how should we  
598 balance the roles of CZOs in developing long-term observational records versus shifting  
599 measurement strategies to advance and test new hypotheses? Fourth, what funding and  
600 management models would enable increased involvement of CZ scientists who are not yet part of  
601 core CZO teams? These four issues are addressed in the next section where we propose a new  
602 model for the future of the network.

## 603 **9 The future network**

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

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

614           Mechanism (ii), campaign-style research, has the advantage of exploring CZ questions  
615 over a range of conditions (Larsen et al., 2015). Such campaigns often focus on material  
616 properties or process dynamics. Campaign-style research can focus many different one-time  
617 measurements, or measurements across a larger spatial scale, than CZOs can routinely  
618 accomplish. Campaigns typically incorporate small teams of researchers.

619           Establishment of centers (approach iii) is another important means to guide and test field  
620 data collection and to probe for deeper understanding by fostering communication and  
621 collaboration among many researchers. However, the CZO approach (iv) is the only approach  
622 that forces diverse researchers to tackle fundamental questions at a single location while also  
623 performing the nine important roles described above. In particular, only observatories provide  
624 the long-term data and the diverse co-located observations from all disciplines that we need to  
625 understand the CZ. By working together with centers, only place-based observatories can knit

626 together disparate views by acting as gathering points for scientists from all disciplines with all  
627 their skills, instruments, and models.

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

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

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

639         Even if the CZOs target this question together, some adjustments to the current topology  
640 of the CZO network should be evaluated and updated so as to promote the emergence of  
641 network-level ideas. Indeed, many other topologies can be imagined (Fig. 5). Many scientists  
642 have similarly considered aspects of what is needed for environmental networks (Leopold,  
643 1962). For example, one topology might be to choose new observatories to fill in gaps among the  
644 current nine CZOs, as shown schematically in the diagram. Another model might be to continue  
645 the current nine CZOs as the future network in order to sustain both their unique observational  
646 records and the theoretical advances these advances enable. Another model might be to choose  
647 nine (or some other optimized number) completely new CZOs, i.e., treating the country as a  
648 blank slate. Another model might be to complete a careful analysis of the current CZOs in the  
649 context of Long Term Ecological Research (LTER) sites and Long Term Agricultural Research  
650 (LTAR) sites and then to extend the network appropriately. NEON should also be part of this  
651 leveraging, as it becomes operational nationwide. A fifth model might be to establish various  
652 “hub” locations and then choose smaller sites along environmental gradients extending out from  
653 the hub. Finally, many CZOs might be funded for research along with smaller satellite sites that  
654 extend from the central CZO.

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

662 The best topology to address these issues is a design like the hub-and-spoke model but  
663 with multiple hubs and a high degree of scientific coordination with the other networks noted  
664 above. In addition, instead of spokes, i.e., lines of satellite sites that extend geographically out  
665 from the hub, we prefer to call these “campaigns”, noting that in some cases these satellites  
666 might indeed be spokes, but in other cases they might be located in vastly disparate locations.  
667 This model would answer the need for long-term measurements (at carefully chosen hubs), the  
668 need for short-term targeted measurements at specific locations both within the U.S.A. and  
669 abroad (carefully chosen campaign sites), and the need for new mechanisms to engage more  
670 investigators (funding to bring in scientists from outside the hub network). This long-term hub  
671 and short-term campaign emphasis has been promoted in the literature by researchers both inside  
672 and outside the current CZO funding framework (Banwart et al., 2012; Larsen et al., 2015).  
673 Fundamentally, the argument for the hub and campaign approach is that the two methods benefit  
674 from each other. Specifically, the hub provides the unique opportunity to dig deep into  
675 understanding mechanisms and process dynamics, whereas the campaign approach provides an  
676 opportunity to test the generality of specific findings, ideas, or theories across some relevant  
677 gradient, e.g., in climate, land use, or tectonic activity while bringing in outside researchers.

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

687 It makes sense for the hubs to be located in settings of broad interest from a scientific and  
688 societal point of view. For example, an urban CZO could be considered. Alternately (or in  
689 addition), the hubs could be located to test specific hypotheses about critical zone structure and  
690 controls across gradients of attributes such as climate or tectonic activity or disturbance. Hubs,  
691 chosen for their strategic and scientific importance, would presumably also be chosen in  
692 recognition of the needs of human resources for education and outreach, and of the need for both  
693 applied and curiosity-driven science. The potential use of hubs as attractors for students and  
694 scientists and platforms for increasing diversity in the Earth and environmental sciences would  
695 need to be stressed.

## 696 **10 Conclusions**

697 We now recognize the critical zone as an entity composed of co-evolving systems that  
698 create the structured dynamic skin of the Earth. We are seeing the first maps of this structure as  
699 they emerge and we are discovering how the structure influences water resources and hydrologic

700 processes, vegetation, ecosystems, erosion, biogeochemical processes, and even regional climate.  
701 Surface and deep processes are connected. A first set of testable models has emerged and now  
702 points to specific measurement programs. But this is only the beginning. While progress has  
703 been made, the central questions remain: what controls the critical zone properties and processes,  
704 how does the critical zone respond to climate and land use change, and how can we use our  
705 advancing understanding to benefit societal needs? These fundamental questions will require a  
706 sustained research commitment. The critical zone is a frontier area of science where only the first  
707 observations have been obtained. New methods, instrumentation, and theory are needed to  
708 continue to grow convergent understanding.

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

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

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731

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

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733	CZOs in the United States	9
734	CZOs worldwide	45*
735	Countries with interdisciplinary field observatories hosting CZ science**	25
736	Papers citing critical zone in keyword WOS as of 2017 <sup>#</sup>	926
737	Papers listing critical zone in title in WOS as of 2017	242
738	Post-doctoral students educated at CZOs in 2015	39
739	Graduate students educated at CZOs in 2015	186
740	Undergraduate students educated at CZOs in 2015	106

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

743 \*\*Giardano and Houser (2015)

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

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749  
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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 Shale Hills	S. Sierra
<b>Land-Atmosphere Exchange</b>									
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
<b>Vegetation and Microbiota</b>									
Structure and function above and below biomass	X	X	X	X	X	Y	Y,Z	X	X,Y
Microbial composition	X	X	X	X	X	Y	X	x	X
ET-species composition and structure relationships	Y	Z	X	Y	Y		Y,Z	X	X
<b>Soil (Vadose Zone)</b>									
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
<b>Saprolite and Bedrock (Saturated Zone)</b>									
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
<b>Surface Water</b>									
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
<b>Age or rate constraints</b>									
Cosmogenic radionuclides	X	X	X			X		x	X
C ages	X	X	X			X		x	
Optical Stimulated Luminescence ages	X								

751 x: instrumentation in place or sampling is occurring, owned and operated by the CZO; y indicates instrumentation is currently in  
752 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  
753 the CZO

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

Model name	Systems modeled	Possible X-CZO application?	CZOs using model
PIHM	Hydrology	x	CR, SH, CL
Flux-PIHM	Hydrology, land/atmosphere	x	SH
tRIBS	Hydrology		LQ, CL
hsB-SM	Hydrology		CJ
VS2D	Unsaturated hydrology		BC
Dhara	Near surface critical zone	x	IML, SH
Optimal sensing	Soil moisture		CL
Hydropedo Toolbox	Soil moisture		SH
OTIS	Streambed hydrologic exchange		SH
Alpine glaciers 1&2d	Ice motion		BC
Fluid exchange	Estuary fluid flux		CR
PHREEQC	Aqueous geochemistry		LQ
WITCH	Weathering	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	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	Water/sediment transport, uplift, weathering	x	SH
PIHM-DOC	Hydrology, dissolved organic carbon		CR, SH
TIMS	Hydrology+microbio/geochem/geomorph/ecology	x	CJ
RHESSys	Hydrology, ecology	x	SS
AWESOM	Atmosphere/watershed/ecology/stream/ocean	x	EL
tRIBS-ECO	Hydrology, erosion, soil C		CL

<b>WEPP/CENTURY-WEPP/WEPP-Rill1D(3ST1D)</b>	Soil erosion, biogeochemistry	x	IML
<b>OpenFOAM/BioChemFOAM</b>	Riverine transport	x	IML
CRUNCH	Reactive transport	x	SH, IML, EL
Delft3D	Surface/subsurface transport	x	EL
Nays2D	Flood	x	IML

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758 Table 4. A few emergent hypotheses from the CZO network

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- 759 1) CZ architecture controls hydrologic and geochemical processes that drive concentration-  
760 discharge relationships in rivers.
- 761 2) The depth to fresh bedrock across uplands landscapes may be predictable from models that  
762 account for regional stress fields, advancing chemical reaction fronts, drainage of the fresh  
763 bedrock, and/or fracturing from freeze-thaw.
- 764 3) Aspect differences can be used to reveal the mechanisms and effects of climate on the CZ.
- 765 4) The deep microbial community is linked to overlying vegetation: microbial community is  
766 distinctly different under agriculture fields, brush, grassland, perennial forest and deciduous  
767 forest.
- 768 5) The deep microbial community is linked to lithology: the microbial community is distinctly  
769 different on granite, basalt, shale, and sandstone.
- 770 6) The deep architecture of the Critical Zone controls water availability to plants and microbial  
771 communities, which in turn influence regional climates.
- 772 7) Subsurface reaction fronts may often be used to map flow paths in the subsurface.
- 773 8) Human impact in intensively managed landscapes has resulted in a critical transition that has  
774 changed the landscape from primarily a transformation-dominated system characterized by long  
775 residence times of water, carbon, and nutrients, to a transport-dominated system characterized by  
776 fast movement of water, sediment, carbon, and nutrients through the landscape into receiving  
777 water bodies.
- 
- 778

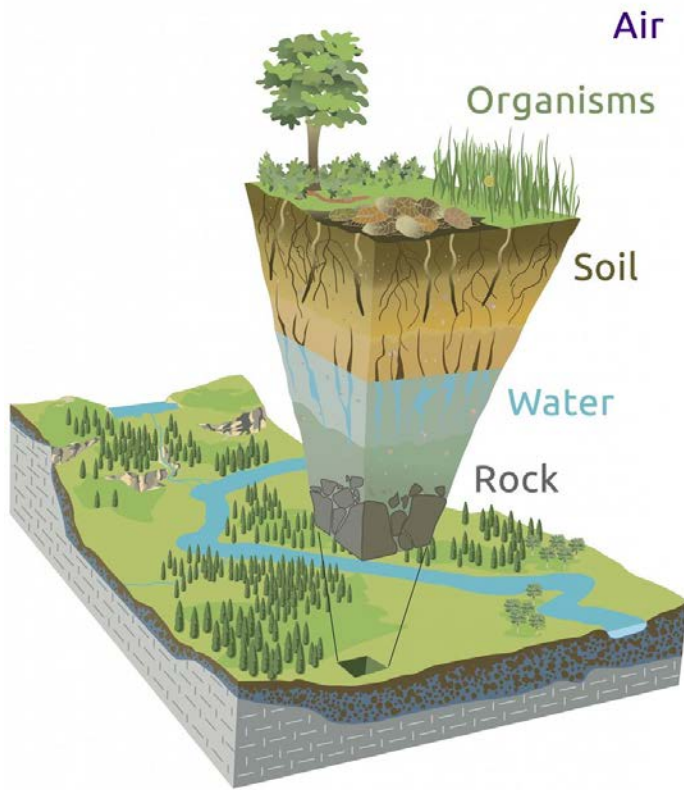


Figure 1. Understanding the critical zone requires harnessing insight from many disciplines on processes and fluxes from the top of the vegetation canopy down into groundwater at all spatial scales across timescales from milliseconds to millennia. Figure reproduced from Chorover et al. (2007), artwork by R. Kindlimann.



Figure 2. The current network of nine Critical Zone Observatories funded in the United States to investigate all aspects of the critical zone. Abbreviations 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).

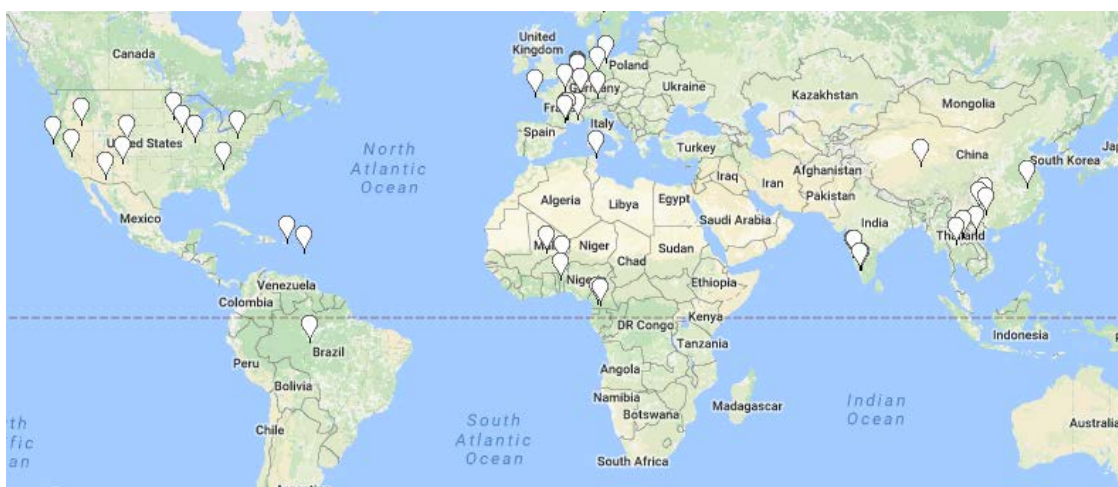
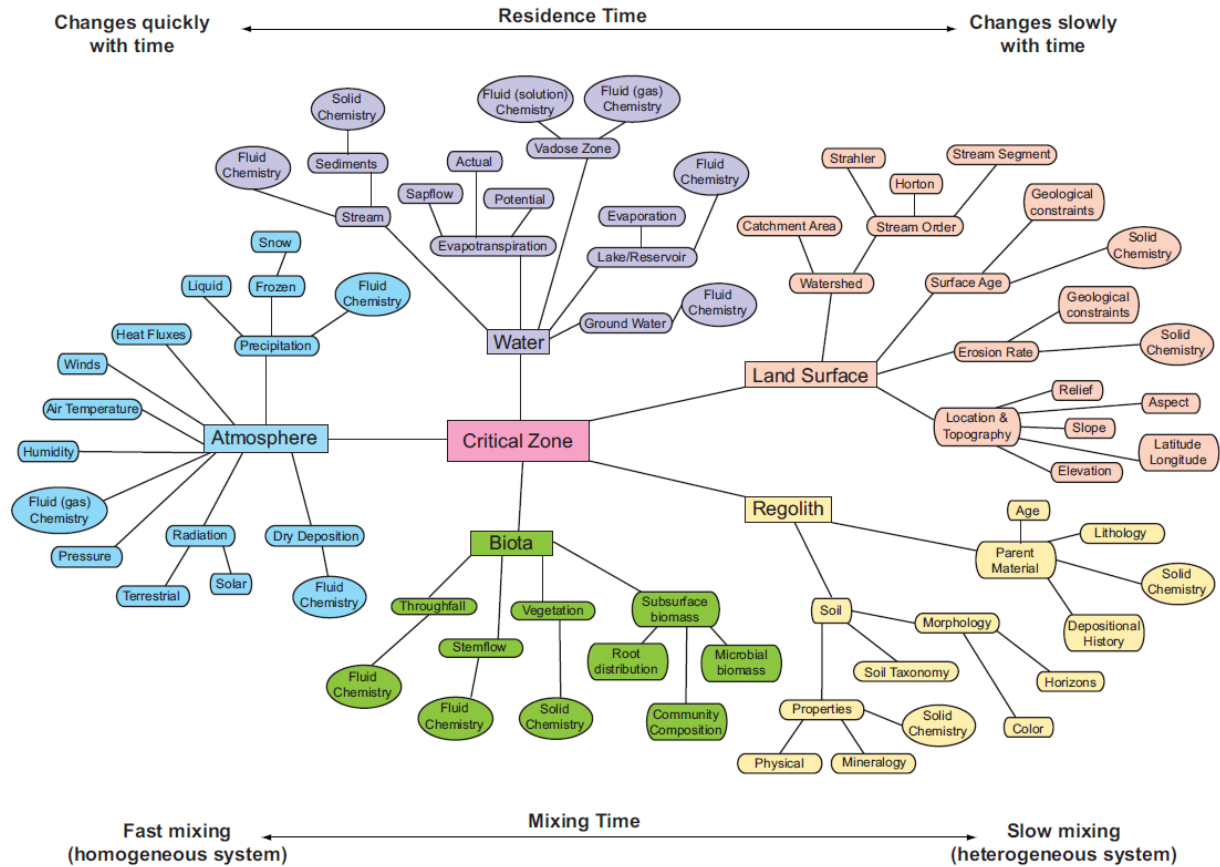


Figure 3. Location map of the 45 CZO locations in the U.S., Germany (TERENO), France (RBV/CRITEX), UK, and China that have been registered on Site Seeker ([http://www.czen.org/site\\_seeker](http://www.czen.org/site_seeker)). The sites outside of Europe that are not in China are all operated by the French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



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

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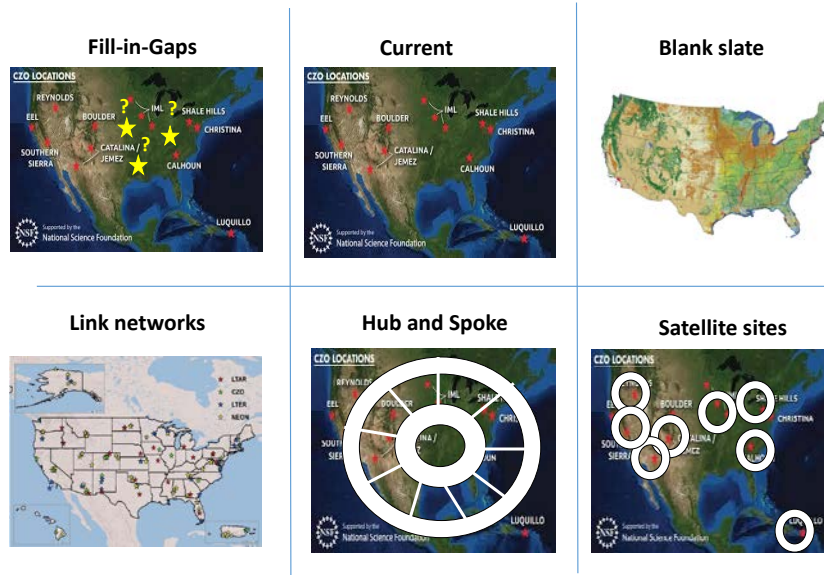


Figure 5. Conformations of a future CZO network discussed in the text. . The most effective topology is likely to be a combination of the observatory framework with smaller campaign-style science as discussed in the text, i.e., a “hubs-and-campaign” strategy.

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