CZO Network Reverse Site Visit, November 14-15, 2016 at NSF

1 Introduction

Background

The Division of Earth Sciences (EAR) within the National Science Foundation (NSF) established a network of Critical Zone Observatories (CZO) to unravel the heterogeneous and complex processes that affect "Earth's permeable near-surface layer... from the tops of the trees to the bottom of the groundwater."[1] Following last year's evaluation of individual CZO for contributions to research, education/outreach, and project governance/management, this Reverse Site Visit review examined the progress the CZOs have made as a whole in establishing a functional, integrated network. The CZO network Reverse Site Visit was held November 14-15, 2016 in Washington, DC. The meeting focused largely on cross-CZO efforts and was attended by NSF EAR staff, CZO principal investigators and early-career researchers, and the Review Panel (Panel).

Five of the nine current CZOs were established in response to the initial solicitation (NSF 06-588). The stated purpose was to "significantly advance our understanding of the integration and coupling of Earth surface processes as mediated by the presence and flux of fresh water." There was no indication of development of a network of CZOs in this initial solicitation. However, development of a 'networked set of CZOs' was central to the 2012 solicitation (NSF 12-575). For example, within the synopsis, it stated: "An overarching goal of the critical zone observatory network . . . is to offer scalable and transferable information that could enhance the scale and scope of the knowledge building and societal benefits that will accrue beyond where the specific CZOs are located." The solicitation discussed coordination among CZOs to address common questions, data management, and educational activities. It also stated the expectations that the CZOs will collect a common set of measurements, use common data management tools, and "serve as a community resource to engage investigators beyond the CZO awardees in CZ research." These expectations were listed in parallel with expectations for individual CZO activities. Five of the initially established CZOs were renewed based on proposals that incorporated these new expectations, and the four additional CZOs were established in response to this 2012 solicitation.

The NSF has made a large investment in the CZO network of approximately $50M since 2013. The majority of the support is derived from the core programs of the Surface Processes Section within the Earth Sciences Division.

The Panel consisted of ten members with expertise across the spectrum of the core Surface Earth Processes Programs that support the CZOs, including hydrology, geomorphology, low temperature geochemistry, sedimentary geology and paleobiology. Additionally, some of the members had served on previous panels evaluating individual CZOs and several of the members have had

[1] From the CZO website at: http://criticalzone.org/national/research/the-critical-zone-1national/

experience (within the past ten years) serving as program officers at NSF. The Panel members are listed in Appendix A.

Charge

The goals of the Reverse Site Visit presented to the Panel were to:

1) assess the accomplishments of the Critical Zone Observatory sites as a coordinated network advancing common directions in science and education; and

2) assist NSF in determining the most productive means to encourage innovative research in critical-zone science.

We found that the presentations and question and answer periods during the meeting were mostly focused on the first goal. This report focusses on our findings reflecting the progress of the CZOs toward functioning as a network and recommendations to improve the network; these are summarized briefly in the "Key Findings and Recommendations" section.

Process

The Panel listened to presentations from CZO investigators over a day and a half. The meeting agenda is in Appendix B. In advance, we were provided documentation about recent activities of each of the individual CZOs and the CZO National Office (NO). The presentations were provided to us electronically at the end of the first day of the meeting. A last minute change in the agenda eliminated presentation of an alternate future vision for CZO research. A series of short presentations by a talented group of early career scientists that were trained within the CZO infrastructure concluded the presentations. These discovery-focused presentations constituted an impressive portfolio of contributions.

This report is divided into sections focused on Research, Education & Outreach, Governance and Management, and Key Findings and Recommendations. The majority of the report reflects Panel answers to questions supplied by NSF. All members of the Panel reviewed and concur with the findings and recommendations in this final report.

2 Research

Innovation

Cross-disciplinary research, mostly within the geosciences, has been moved forward considerably by efforts at the individual CZO level. Accomplishments in the last year include publishing (291 papers/chapters), theses (57), and conference abstracts (200). Output has been increasing since establishment of the network four years ago. CZ research had a strong presence at the AGU Fall Meeting in 2016, with the Union Session on CZ research and 46 contributed abstracts. While not necessarily a new science, the transdisciplinary nature of the CZO work is novel and requires effective communication across traditional discipline boundaries. The nascent cross-CZO research efforts show promise in terms of innovation that goes beyond that in the traditional geosciences. Harnessing the power of the CZO network and building on the accomplishments of one "grand challenge" is a good approach to building innovation. The current effort to investigate the development and structure of the critical zone (CZ) is a good example.

The crop of early-career researchers is impressive and shows that the cross-disciplinary approach has longevity. The fact that CZOs are developing around the world demonstrates that the idea has appeal and substance across societies.

Unifying Framework of Coupled Processes

The current network of CZOs was not designed to optimize the cross-site comparisons needed for developing unified theories of CZ processes. Proposals responding to the initial CZO solicitation were selected based on their individual merit without consideration of network complementarity. Nonetheless, unifying theoretical and conceptual frameworks have begun to emerge. These unifying hypotheses are now driving research priorities at existing sites and will probably influence the direction of future proposals for new sites and new research.

Two good examples of new unifying frameworks are CZO research efforts related to: the evolution and structure of the CZ, and the mediation of hydrologic partitioning and the concentration-discharge relationship by CZ structure. These two examples of new frameworks take advantage of the rich data sets (hydrologic, geochemical, geophysical and biological) collected at CZO sites and the strong cross-disciplinary spirit that has begun to emerge among CZO researchers. Both the multi-dimensional CZO data sets and the cross-disciplinary thinking of the teams have enabled fresh evaluation of these two long-standing problems, and the potential for CZO sites to collect common data and measurements can enable hypotheses emerging from one site to be investigated across the network.

These and other unifying frameworks should be developed to represent a broader range of properties by selecting locations for future CZO sites that best fill gaps in the characteristics of the existing network. For example, it is valuable to consider pairing depositional sites with the existing erosional sites, perhaps simply by locating sites downstream, because the existing set of CZO sites provide little opportunity to study different depositional environments.

Much of the data characterizing CZO sites show changes over different time-scales. It may be too early to clearly identify which trends are caused by climate change and which are caused by shorter duration cycles of precipitation and temperature. It will be important, going forward, to come up with an approach to identify the causes of these patterns.

System-level Models

Modeling at the individual CZO level is still a work in progress, and cross-CZO modeling is mostly at the conceptual stage. Development of theoretical and conceptual frameworks, such as those described above, will improve predictions of how the CZ responds to exogenous changes. The capability to test theoretical and computational models across CZOs will depend on the organization and management of data, as discussed in "Standardization of Data and Metadata." Although models are powerful exploratory and predictive tools, the development and use of models for CZO network-level science is currently limited by dedicated resources, the lack of centralized staff and resources dedicated to modeling at some sites, and the lack of a formally structured modeling framework. Development of advanced modeling and analysis capabilities should be a sequential process, focusing first on community-building through a series of workshops. The workshops should draw on both CZO investigators and non-CZO investigators who have relevant synthesis and modeling expertise. The workshops should address questions such as what processes can the CZO network empirically address across sites now, what modeling capability can be used in the synthesis, and what are the challenges, opportunities, and strategies available for the next 3-5 years for synthesis and modeling? To sustain synthesis and modeling activities into the future, an ambitious investment is needed to support and train the next generation of CZO quantitative modelers. Almost all of the CZO research on hydrologic, geochemical, and ecological process will provide better models of how these processes respond to shifts in climate as well as exogenous forces from local human development.

Common Measurements

A cross-CZO group of researchers examined common measurements made by the CZO network in a document titled "Common Critical Zone Observatory (CZO) Infrastructure and Measurements" (May 5, 2015).[2] The categories of measurements included those applied to the atmosphere, land surface, vegetation and microbiota, soil, saprolite and bedrock, surface water, and age or rate constraints – essentially all components of the CZ. Appendix C contains more specifics on the types of common measurements. The measurements are aimed at examining the following CZ processes: the evolution of regolith and drainage valleys; rates of soil production, erosion, and deposition; event-based and continuous fluxes of energy, water, solutes, and sediment across CZ interfaces; and changes in storage/budgets of energy, water, solutes, and sediment at the catchment scale. The management and organization of common measurements and other CZO data is addressed in Standardization of Data and Metadata.

Although interest in measuring the movement of water and solutes across CZ interfaces was mentioned, no measurements were listed for characterizing the hydraulic properties of aquifers (e.g., hydraulic conductivity, transmissivity, sustainable yield) or identifying preferential pathways, especially in fractured bedrock. In general, characterization of the saturated zone has received less attention than characterization and measurement of the vadose zone. In fact, the word "aquifer" is rarely seen in CZO materials. A recent cross-CZO paper by Brooks et al. (2015)[3] makes an argument for conducting more work on hydrological partitioning in the CZ. A 2015 National Academy of Sciences report reviews characterization approaches for fractured media and discusses promising future techniques.[4] In addition, some CZOs have managed to capture short-term events (e.g., during or immediately following floods, snowmelt, fires), but more could be done to examine the importance of these events versus longer-term processes in shaping the evolution of the CZ. Examples include more work on storms, which are expected to become more intense with the changing climate, and El Niño/La Niña events.

On the other end of the temporal spectrum, little to no emphasis has been placed on examining ancient CZs and soils, and translating between ancient CZ records and the processes examined in

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[2] Available: https://criticalzone.org/images/national/associated-files/1National/CZO_Common_Measurements_5-5-15.pdf

[3] Brooks, P. D., Chorover, J., Fan, Y., Godsey, S. E., Maxwell, R. M., McNamara, J. P., & Tague, C. (2015). Hydrological partitioning in the critical zone: Recent advances and opportunities for developing transferable understanding of water cycle dynamics. Water Resources Research, 51(9), 6973-6987. Abstract available: https://arizona.pure.elsevier.com/en/publications/hydrological-partitioning-in-the-critical-zone-recent-advances-an-2

[4] Characterization, Modeling, Monitoring, and Remediation of Fractured Rock (2015). Available: https://www.nap.edu/catalog/21742/characterization-modeling-monitoring-and-remediation-of-fractured-rock

modern CZs. Paleo CZs are important because they record past processes on the Earth' surface. They provide a record of climate, biology, and rock interactions and are important reality checks for modeling past climate. The fact that most CZO sites are erosional rather than depositional environments could be a factor. Paired measurements in depositional and erosional areas within a given CZO could be helpful in filling this gap. The new cross-CZO effort to identify controls on CZ structure is a move in the right direction. Another approach to understand fossil records would be to take cores in depositional areas.

Critical Zone Applied Research

The potential is high for producing CZ research outputs that are important for human health, human safety, and environmental services – and for decision making at many levels of government. In general, this aspect of CZ research is still in development, but most CZOs have at least one example of how their research has been applied or could be used by decision makers (see Appendix C for examples). Some of the aspects of critical-zone research that are most important for society include investigations related to natural and human-caused disasters (fires, droughts, floods); the effects of climate change on water quality/quantity and forest and soil health; and the effects of large-scale environmental alterations (e.g., agriculture, fossil fuel development) on critical zone function. Understanding how ecosystems respond to storms, drought, and climate variability, for example, can help governments design effective methods for capturing and storing water while maintaining in-stream flow. Value, which can be monetary and non-monetary, is an important part of innovative research, and the work on ecosystem services at the individual CZO level is a good example (see Appendix C).

More focus on and evaluation of aquifers would add enormously to the applied aspect of CZ science, especially in relation to water supply. The proposed approach to use CZ structure to explain hydrologic partitioning could result in a greater focus on aquifers.

Incorporating the value of areas that are more resilient to climate change would benefit the CZ services concept. For example, the Catalina-Jemez CZO has found that north-facing slopes tend to have thicker soil development and maintain groundwater levels and have been more resilient to disturbances such as forest fires, although their findings also indicate that post-fire regrowth is slower on north-facing slopes.

Improving predictions is a key goal that would enhance applied CZ research. How can understanding CZ processes help us plan and prepare for the future? One example is using CZ research and observations of how climate change affects all components of the CZ to improve climate models. What is missing in the models that could modify the results in a substantial way, and how can climate models be redesigned to better reflect interactions across the CZ? Another example of how CZ science could be used to improve predictions is examining how natural hazards and man-made alterations to the CZ can affect water quality, water quantity, soils, and vegetation. What changes can be expected when CZ processes are modified, and how can adverse effects be avoided or minimized?

Integration with the Greater Research Community

Increasing the general awareness of CZ science and attempting to engage new scientists from the greater research community is one of the four major goals of the CZOs as presented by PIs speaking for their respective research teams at the Reverse Site Visit. They laid out a list of ongoing and other activities to be accomplished by 2018 (end of this round of funding).

As for the future, the plan that was presented to the Panel is to:

1) Publish a white paper that articulates the vision of collaborative interaction among CZO/Long Term Ecological Research (LTER) network/National Ecological Observatory Network (NEON); establish at least one collaborative activity between the CZO and LTER networks.
2) Enhance the National CZO website to highlight opportunities to increase participation by broader scientific community.
3) Host an open CZ science meeting that promotes collaboration with broader scientific community (details were lacking).
4) Publicize the new CZ network mission, values and vision "To discover how Earth's living skin is structured, evolves, and provides critical functions that sustain life" (details were lacking).

The current CZO research outlet is AGU-centric because AGU is the "meeting of choice" for researchers from the broad range of scientific disciplines (hydrology, meteorology, geochemistry, biogeochemistry, atmospheric geochemistry, soil science, microbiology, geophysics, botany etc.). But, in terms of the reaching the greater research community and engaging them in CZO activities, the CZ network needs to reach out and actively involve those that do not normally attend AGU because of practical reasons such as the great expense involved, but also the perception (rightly or wrongly) of the community not being inclusive. A logical target for accessing the greater research community is the regional and national meetings of the Geological Society of America, where there is higher proportional attendance by small and community colleges, state and federal agencies, and students. There is also likely to be a more diverse population at these smaller more local meetings. In addition, NSF could institute a competitive process for outside researchers to collaborate with the existing CZO network, for example, using a "Dear Colleague Letter" approach. In this way, the most promising ideas from outside the CZO network could increase internal innovation. However, improvements in the functioning of the CZO network should precede new efforts to bring in outside researchers.

Standardization of Data and Metadata

CZO sites designed originally as standalone projects each established their own data management practices. There is no system in place, at present, for easy data access and data exchange between the CZO sites or with the broader scientific community. Importantly, there are few agreements for metadata standards and/or protocols. Little information with respect to ongoing data management for the network was mentioned in the presentations. The NO is not charged with managing data. However, the Organizational Chart of the CZO network shows a "Data Managers Committee" that is in line to receive data from the network of CZO sites. That Committee then sends data to the "Data Management Committee." The Panel did not see evidence of this happening. The PIs acknowledge that amassing large amounts of data is a strength of the CZOs, but given how complex the data are, they are still challenged in publishing data online and making it transparent to all. Thus, lack of integrated data management is an acknowledged weakness and the CZOs recognize the need for a fulltime person for data management for the network. It will be hard to move forward on cross-CZO modeling if data management is not being handled effectively across the CZOs. There are various opportunities within NSF programs for the CZOs to do this—EarthCube, Geoinformatics within the

GEO directorate and various programs within the Computer Science directorates. The CZOs have not taken advantage of these programs to develop a strong cyberinfrastructure platform that would serve the network.

Limited progress has been made toward standardization of data and metadata. All sites now post basic meteorological and hydrologic data in consistent format (IML is on own site only). Common vocabulary is being used. Southern Sierra and Susquehanna Shale CZOs have some data sharing activities. However, for example, in the area of stream water chemistry, different units are used (e.g., micromolar vs milligrams per liter), in some cases the units are not specified, some CZOs place analytes horizontally and others in a pull-down menu, some locational information appears to be missing, and the methods for searching and downloading data are different. The work entailed in coordinating these disparate datasets, even within a subfield such as water chemistry, is enormous. And currently, the Panel could find no datasets with combined information from multiple CZOs, aside from some hydrologic data entered in the CUAHSI data catalogue.

To remedy the lack of a cross-CZO data management scheme, the CZOs do not need to reinvent the wheel; they can adapt data management systems used by others, such as NSF's Interdisciplinary Earth Data Alliance (IEDA), CUAHSI, and others. Recent efforts to collect data across CZOs is showing progress, including the optional use of the Observations Data Model Version 2 (ODM2) for local data management,[5] but a data management scheme is needed for the network.

Research Summary Statement

Cross-disciplinary research, mostly within the geosciences, has been moved forward considerably by efforts at the individual CZO level. A stronger effort is needed across the network to take full advantage of the observatories and enhance innovation. Some recommendations include:

- Efforts to collect and evaluate common measurements across CZOs are improving. Additional proposals for common measurements should also be considered. Some progress has been made on standardizing data and metadata across the CZO network, but additional effort is needed.
- Network level modeling efforts are not in evidence. Data integration across CZOs will be needed before a cross CZO modeling effort will be successful.
- Pairing measurements in depositional and erosional areas within a given CZO, perhaps simply by locating sites downstream or incorporating efforts in depositional areas, would help fill the gap in studying fossil CZs.
- Network level effort to apply fundamental CZO research to pressing societal issues is needed. Topics addressed could include aquifer dynamics and water supply, short-term hydrologic events, resilience to climate change, and improving predictions (e.g., for climate models), among others.
- Integration with the greater research community could be enhanced by encouraging participation of researchers outside the system, using a Dear Colleague Letter or other approach, and expanding the types of meetings attended by CZO network researchers (e.g., GSA regional and national meetings).

[5] See http://criticalzone.org/national/data/odm2/

- Some progress has been made on standardizing data and metadata across the CZO network As we have seen in some of the cross CZO research efforts, cross-CZO data is of tremendous value in advancing and unifying our understanding of the critical zone. The cross-CZO data must be readily discoverable and accessible by the broader scientific community in a form that facilitates cross-site comparison and analyses. Effort must be focused on making significant, additional progress on data standardization and availability across the CZO network.

3 Education & Outreach

The individual CZOs have a wide variety of education and outreach efforts, building on local and regional issues and leveraging and partnering where appropriate. The CZO NO has an opportunity to coordinate and build off these efforts, enhance the reach and impact of CZOs, and engage a wider cross section of the academic and educational communities than can be done by individual sites. An improved effort at the national level would bring more CZ science to the broader public by utilizing the full breadth and diversity of the network.

The CZ NO is becoming more actively engaged with the broader community through AGU sessions, town halls, and anecdotally via sponsorship of cross-site workshops. The CZO network is progressing with science communication to stakeholders, and we recommend that these efforts in engagement and outreach extend beyond what individual sites have accomplished so far. Highlights in this regard are the CZ curricula that have been developed at several levels. We emphasize the necessity of making these centrally available in addition to being available on individual site websites (SERC, InTeGraTe, etc.).

There is clear excitement about student engagement at a range of levels: K-12, undergraduates, graduate students, even post-docs and early career faculty. The CZO network is thus building a strong cohort of students and researchers engaged at individual CZO sites who are developing a keen sense of community. More needs to be done to reach out to under-represented groups: minority, women, and 1st-generation students and scientists. Programs that engage these groups at individual CZO sites should be considered for use as exemplars for other sites.

Overall, the role of the NO in coordinating an education and outreach agenda is not clear. Are there plans? Is there an organizational strategy or flowchart? It is not clear that the CZO network has a strategy for effective outreach, for interactions with K12, or for communication outside the network. There are site specific efforts and these attempts are clear, but a network strategy that organizes and synthesizes all the site specific efforts is absent. This is important for recognition beyond individual CZO sites and for promoting CZ research within and beyond NSF.

Although there is a strong push for engagement with the public at local/regional levels, it is not clear how the CZO network will take site-specific engagement efforts to the public writ large. This is a difficult task given that the messages are necessarily local or regional in scope and interest, and it is hard to make these into more generalizable public engagement efforts. Doing so is crucial because most Americans live in urban areas, or in regions and geographies that do not look like CZOs. The "CZO in my backyard" concept will not likely resonate with large majorities. The CZO network and NO must figure out ways to make CZ science generally attractive and valuable to the public. There is a keen need to demonstrate 'science for society,' and CZ science especially can and should show relevance to human health, natural hazards, resources (agriculture and water for example), as well as CZ services. There seems to be little development and integration beyond local and site-specific fragments.

With regard to science communication with stakeholders, we propose that a comprehensive strategy be developed. It is important to recognize and demonstrate that the approach is not ad hoc. The CZEN website and SiteSeeker are great tools; unfortunately, it is not clear how these are being promoted and how they can be made highly visible. Similarly, the Newsletter is great, but how do stakeholders, the general public, students, policy-makers and others discover this? What is the network's strategy for alerting interested parties to CZO developments?

More cross-CZO work is needed to translate the fundamental research results from the CZO network to accessible content for stakeholders. Expanding the concept of ecosystem services to CZ services is a high-profile example of a finding related to CZ value. In parallel, a network level effort to identify stakeholder needs with respect to cross-CZO research themes could be useful. Although the CZO network currently has no direct collaborations with social scientists, future collaborations with social scientists could lead to new perspectives on the value of CZ (ecosystem) services, including intrinsic societal value. Ultimately, the collaboration could improve communication and outreach to stakeholders.

To better welcome new researchers into the CZO fold, the CZO network should offer guidelines to outside researchers to help them understand how to work at CZO sites. The CZO network and NO could take a systematic approach to better communicate the parameters for working at CZOs. This would set expectations and, importantly, help to solicit broader outsider interest.

Assessment of the network's education and outreach activities is lacking, almost entirely. This includes assessment of education, outreach and stakeholder engagement efforts across the network. We recognize the lack of time and expertise across and within CZO sites; however, many opportunities exist to partner or leverage. Initial steps in this regard have drawn on marketing research. A significant portion of CZO funding is going into education and outreach efforts, but at present there is no way to measure if that funding is being spent effectively.

Education & Outreach Summary Statement

There is much potential for the NO to build upon, coordinate and assist with assessing the many high-quality education and outreach efforts that have been established by the individual sites and science teams. The Panel suggests that the NO focus on developing a strategy that clearly lays out how it can coordinate communication, promote community use and awareness of CZOs, and lead effective education and outreach assessment activities.

4 Governance and Management

Our comments emphasize the NO because it is central to the management structure of the CZO network.

There is potential for leadership from the NO to better coordinate the inter-site, overarching scientific research and the collective education and outreach activities. To date, the NO has not been as effective in management of the network as it should be, in part due to its being relatively new and added after most of the CZOs were established, but also due to other issues that are discussed in this section. The CZO network appears to be too ad hoc to be considered well-coordinated, and the NO should play the leadership role in developing the necessary benchmarks and milestones for integrating the sites. Efforts at coordination, such as the website, which is the portal for the CZOs to the wider community, should be expanded upon and developed into a more effective platform.

The NO does not yet have a well-developed and articulated governance structure to support CZO network activities. Whether or not this under-defined structure is due to the fact that the NO was added after most of the CZOs were already established as stand-alone PI-driven sites is not clear, but this should be one of the primary responsibilities of the NO and should be developed at a sustainable level. Successful governance is emerging due to the intrinsic cooperation of PIs, but the NO does not seem to be coordinated with the PI-driven, loose affiliation that has grown organically over the course of the CZO program.

The organizational chart is unclear and does not show the connection of the NO to the other elements of the CZOs. Management elements seem to exist in the form of the CZO network Implementation Group (NIG), the CZO Executive Committee, and the CZO Steering Committee, all of which were mentioned in various documents. However, the elements were not well connected to each other or to the organizational structure at large. The Panel did not see much evidence of the NIG in the various documents or on the website, and it was not identifiable on the NO organization chart. In fact, the Panel was not sure if the NIG was the same as the CZO Executive Committee or how the Executive Committee differed from the Steering Committee. The function and membership of the Steering Committee was not clear, and its relationship within the organizational structure was vague. The Panel was also concerned that while there is money in each site's budget to fund attendance to NIG meetings, there was no clear evidence of who is a member of the NIG group and when they met. The Panel thought that this lack of clarity might be due to the nature of the evolution of the management and governance of the CZOs and the evolution from a loose aggregation of stand-alone sites to a network. The Panel was unclear what the Steering Committee does and who are the current members. On the NO website, the Steering Committee was listed as Gordon Grant, Mary Firestone, and Lou Derry, but the last report that the Panel could find was in 2012, which made it unclear whether this was their last report prior to 2016 or if they were still meeting and acting on behalf of the CZOs. In addition, it was not clear if the Steering Committee is supposed to be an external entity and how its membership is or was established. It is not clear what the difference is between the NO Director and the NO Coordinator. Overall, even as the CZOs struggle with the issues of governance, the NO remains a weak presence as a coordinating entity.

The Strategic Plan that emerged from the February 2016 Strategic Planning Workshop is a good start on a workable framework for operation of the network. More specifics are needed, but the plan provides an initial basis for developing a long-term observatory strategy. Although the Strategic Plan was developed, the status of its implementation was not clear. The NO could do much to help coordinate the implementation with respect to benchmarks and milestones to allow the CZOs, NSF and the broader scientific community to assess the progress.

Although some progress has been made, there is little evidence of actual management of the network by the NO. Most of the information presented about NO activities at the Reverse Site Visit was on Education and Outreach efforts, which are evaluated separately in this report. The Strategic

Plan is considered skeletal and does not have strong actionable items with benchmarks and milestones to be evaluated rigorously by the Panel at this time.

Perhaps most surprisingly, there is an extremely limited role in data management played by the NO, and this is where the NO should be highly effective in coordinating across sites and creating better outreach to the community at large. For example, the NO should be examining the data management approaches used at individual sites, determining best practices and standardization approaches, and helping other sites to adopt those practices. The NO should be involved in providing community-driven data management policies as well as linkages to, for example, EarthCube and data platforms and systems. The NO should lead in linking data to and from other networks such as the LTER, NEON, Long Term Agroecosystem Research (LTAR) network, and the Arctic Observing Network (AON). While there seemed to be some evidence of efforts in data management leadership, there was not a comprehensive strategy articulated at the Reverse Site Visit.

Governance and Management Summary Statement

In summary, while perhaps well-intentioned, the NO does not seem to have made substantial and expected progress in developing, leading and coordinating the CZO network. Specific actions to improve governance and management of the network are: 1) implementing a shared governance structure with well-defined benchmarks and milestones, 2) effectively coordinating data management strategies, 3) develop a more effective web platform with search capability among the sites, 4) have an active role in reaching out to the broader community of scientists with information about possible collaborative activities, and 5) develop a plan for recruiting under-represented groups at individual sites and across the CZOs.

We propose the following list of actions to create a more effective management framework for the CZO network. Top-down management from the NO is not the goal, but coordination is the aim. Actions that could be taken now include the following:

- The NO should refine the governance structure and the roles of the Steering Committee versus the Executive Committee and the NO leadership.
- The NO should do more to capture innovations at the granular, individual-site level and propagating them through the entire CZO network.
- The NO can lead the CZOs toward better collaboration with existing networks; LTER, LTAR, AON, and NEON. Opportunities to attract funding for collaborative activities among them should be explored.
- The NO could manage external innovation and collaboration across the CZOs that would bring new investigators into existing sites. This effort should be supported by additional funding from NSF through possible Dear Colleague Letters or other mechanisms.

5 Key Findings and Recommendations

The Panel concludes that while individual CZOs have been remarkably successful, the expectation of a coordinated network of CZOs remains unfulfilled. Individual CZOs have significantly advanced critical-zone science, enhanced interdisciplinary research, published hundreds of manuscripts, trained many students, and developed an outstanding cadre of early career faculty. In contrast, successful cross-observatory activities have been limited, opportunistic, or ad hoc. The Panel recognizes that network organization was added after the first set of CZO awards. Nevertheless, too little attention has been given to organizing those cross-observatory activities that best lend themselves to networking, such as education and outreach, data management, coherent and comprehensive cross-observatory measurements, and common critical-zone models. There is only a nascent effort at approaching broader research questions that a network can address. Integration with researchers from the wider critical-zone community is up to individual CZOs and remains informal and largely ineffective. If CZOs are to become integrated with this wider community, address broader research questions, and take advantage of other networking opportunities, the network must become stronger. It must become more than the sum of the individual CZOs, augmented only by conventional channels such as co-authoring publications, attending joint scientific meetings, and informal collaboration. The network research ideas that were presented during the Reverse Site Visit indicate potential to the Panel, but progress toward formally advancing and enhancing these ideas is slow considering the nearly four years that the CZOs have been intentionally encouraged to operate as a network. **In order for the CZO model to function to its full potential, the CZOs must function more often and more effectively as a network**. Below we make several key recommendations that may be able to accelerate this process and improve the chances for success.

An ideal CZO network requires a broader range of geoenvironmental conditions than those represented currently in order to cover the breadth of questions of interest to CZ scientists. The original CZO awards did not consider development of a network. Consequently, the current CZO network does not represent sufficient diversity of attributes, such as bedrock (or parent) material type, erosional versus depositional environments, and human development and land use. Igneous bedrock and forested lands are highly represented compared to other types of bedrock substrates and land uses. All CZOs, with one exception, emphasize an erosional environment. All the CZOs are in areas of low human development, and most experience more moderate or indirect anthropogenic impacts (IML and Calhoun excepted). Observatory approaches to broader conditions that build on existing networks (AON, LTAR, LTER, NEON) may be beneficial. Alternative approaches that complement the current observatory model should also receive consideration.

The CZO network should include research to characterize and interpret deep time CZ records. Such research could be incorporated in existing CZOs where depositional records are present (e.g., at downstream locations or using deep cores) or at other sites where the geologic, paleoenvironmental and paleoclimatic contexts are well known.

The CZO network would benefit from the involvement of more scientists from outside the network; these scientists also have a high level of interest in CZ science. Accessibility is critical to success, and the network should do more to encourage contributions from outside investigators. Such inclusivity will gain the benefit of new ideas and also create a broader community that embraces the CZO concept, even while the actual number of CZOs is far fewer than the number of institutions involved. The CZO network is a resource to the scientific community, but without greater access the value of the resource will be questioned. Inclusion of the broader community in activities of the CZO network would support the future strategic planning for CZ science that reaches beyond the set of funded PIs and considers approaches that complement the current observatory model. Other NSF-supported observing networks (AON, LTAR, LTER, NEON) have issued Dear Colleague Letters to initiate and support innovation from outside the network. The Panel recommends that, after improvements in network function, NSF consider this and other approaches to enhancing participation by scientists from outside the CZO network.

The current National Office (NO), while well intentioned, does not appear to have made substantial progress in developing, leading, and coordinating the CZO network. Specific actions that could have been pursued, or pursued more effectively, include 1) implementing a shared governance structure with well-defined benchmarks and milestones, 2) effectively coordinating data management strategies, 3) developing an effective web platform that is searchable among the sites, 4) playing an active role in reaching out to the broader community of scientists with information about possible collaborative activities, and 5) developing a plan for recruiting under-represented groups at individual sites and across the CZOs. These are among the many things that could be done to more effectively develop the CZO network and were part of the charge of the NO. Based upon the Reverse Site Review, the Panel felt that top-down management from the NO is not an appropriate goal, but coordination and leadership of network activities should be the aim.

Restructuring of the network's governance and the way in which the current NO functions and interacts with the individual CZOs are needed. The organizational structure of the CZOs with the post hoc addition of the current NO is not working; the roles and responsibilities of the members of the shared governance structure (Executive Committee, NO, and Steering Committee) towards defining and meeting network goals are unclear, and thus, the NO has not achieved its potential. There are two important changes that must be realized. The shared governance structure needs to be recast with well-defined roles and responsibilities for the members. Additionally, leadership of and administrative support for the CZO network must be carried out by a strong and visionary team: this could be a reorganized NO or a new entity with a different name. So as not to imply that the current NO model must be the configuration for the future, we adopt here the neutral term "Network Coordination Administration" (NCA). The NCA would perform coordination activities across the network to benefit the individual CZOs, the broader research community, and the general public. The NCA would capitalize on the opportunity presented by the network to create model programs, including aspects of education, outreach, and overall data management, while also lifting administrative burdens from the CZ researchers. Whether the leadership role is assumed by a reconfigured NO or a replaced by a new NCA, the new leadership configuration should be created in consultation with CZO researchers and NSF. If it replaces the NO, it is possible that the NCA will exist in a separate stand-alone office much as the NO does now. It is also possible that NCA staff could be distributed among the CZO teams with staff specializing in, for instance, data management or education and outreach for the network residing within individual site research teams rather than residing in a stand-alone office.

The NCA should play a leadership role in facilitating network level functions for the individual CZOs. The Panel recommends that the NCA focus on developing a strategy that clearly lays out how the NCA can coordinate communication, promote the use and awareness of CZOs by the broader research community, improve data management and accessibility, enhance and assess education and outreach activities, and facilitate recruitment of underrepresented groups, including minorities, women, and first generation students and scientists, across the CZO network. The Panel emphasized these areas in which an effective NCA would facilitate network function and associated community science and greatly strengthen the CZO program.

The NCA should also initiate cross-CZO outreach efforts that identify, examine and communicate the societal value of the CZ. Each individual CZO has at least one example of a research outcome with immediate applicability to a pressing problem. A network-wide effort, such as the one on ecosystem services, has not yet borne fruit. Understanding aquifer properties and how the critical zone responds to storms, drought, and climate variability, for example, can help governments design effective methods for addressing future water supply issues. More cross CZO-work is needed to apply the fundamental research conducted at the individual CZOs to issues of recognizable societal importance and value.

The CZOs, led by the NCA, should place a high priority on making data available to the broader scientific community in a consistent and transparent manner using readily accessible formats. The Panel determined that barriers to identifying CZO data sets remain, even for the list of 'common measurements' from the CZOs. The CZOs should avail themselves of the appropriate data management structures for different types of Earth sciences data that have already been developed, such as CUASHI for water flow and water quality time-series data. While this might be happening now, it needs to be fully developed for all sites and made a priority. The NCA has a crucial role to play in facilitating data management and accessibility. The NCA should lead the effort by providing information and assistance to CZO PIs and an explanatory framework to investigators outside the network. Further, the CZOs should be taking advantage of other NSF funding opportunities within programs like EarthCube and Geoinformatics as well as those relevant programs in the Computer Science Directorate to fund cyberinfrastructure development for the CZOs.

Appendix A. List of Review Panel Members

Richelle M. Allen-King, Professor, Department of Geology, University at Buffalo, State University of New York.

Gail. M. Ashley, Distinguished Professor, Department of Earth and Planetary Sciences, Rutgers, the State University of New Jersey

Charles F. Harvey, Professor, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology.

Janet S. Herman, Professor, Department of Environmental Sciences, University of Virginia.

Ann S. Maest, Vice President, Buka Environmental, Boulder, Colorado.

Lisa Park Boush, Professor and Director, Center for Integrative Geosciences, University of Connecticut.

Steven Petsch, Associate Professor, Department of Geosciences, University of Massachusetts Amherst.

Jennifer Saleem Arrigo, Program Specialist, University Cooperation for Atmospheric Research, and affiliated Program Manager, NOAA Climate Program Office.

Robert L. Sanford, Jr., Professor, School of Earth Sciences and Environmental Sustainability, Northern Arizona University.

John L. Wilson, Professor Emeritus of Hydrology, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology.

Appendix B. CZO Reverse Site Visit Agenda

CZO Network Reverse Site Visit

Location: National Science Foundation, Stafford II 555

Monday, November 14, 2016

8:00 AM	Refreshments Available
8:30	Welcome and Introductions; Brief Overview of the CZO Program
9:00	Synopsis of accomplishments from each CZO site
	Each site will have 6 minutes (2 slides: 1 research, 1 education/outreach)
	15 minutes of Q & A follow all presentations
10:15	Break
10:30	Network accomplishments: Big ideas for research
12:00	Lunch
1:00	Network accomplishments: Cross CZO Education and Outreach
2:00	Structure and management of CZO network
3:00	Vision for the future
3:30	Executive session, discussion and report writing

Tuesday, November 15, 2016

8:00 AM	Poster Set-up
8:30	Review committee briefs CZO sites on initial findings
10:00 – 2:00	Symposium on Critical Zone Research: The Next Generation

10:00 – 10:45 "Lightning" presentations by CZOs on select new discoveries

~~10:45- 11:00 A vision of the future of critical-zone research~~ (Cancelled)

11:00- 2:00 Poster presentations from the critical-zone frontier

11:00 – Review committee meets as needed to continue preparation of draft report.

Appendix C. Additional Information on CZO Research

Research Question 1. Examples of Cross-CZO Investigations

Six cross-CZO investigations[6] are currently under way – all dealing with CZ structure, which is the most fundamental of issues. All or most of the CZOs are working on carbon storage and dynamics. As a result of cross-disciplinary work, five theories have been developed and are currently being tested to explain the development of the CZ and the observed depths of the regolith. See: http://criticalzone.org/national/research/cross-czo-studies-1national/ for more detail.

The next major cross-CZO effort is focused on understanding how CZ structure (physical, chemical, biological) controls hydrologic partitioning. The work by Noah Molotch (CU Boulder) and Ciaran Harman (Johns Hopkins), described in the Fall CZO newsletter, on comparing how CZ physical, chemical, and biological structure determines stream flow quantity and composition seems like the kind of big-picture thinking that is needed for innovative research.

In addition to the cross-disciplinary research, five theme groups have formed that are examining CZ evolution, concentration-discharge mediation, trees, biogeochemistry, and microbial ecology. The work currently under way to investigate fluid flux in trees is a novel way of completing the water budget for a given site.

Research Question 4. Common Measurement Specifics

The soil/vadose zone CZ component had the largest number of measurement categories, including solid and fluid measurements. Nearly all the CZOs were using or had plans to apply these soil measurements. Examples of solid phase soil/vadose zone measurements used at the sites included organic matter content, elemental composition, mineralogy, soil texture and physical characterization, and isotopic composition. Fluid phase vadose zone measurements include soil moisture, temperature, solution chemistry, and gas chemistry, and rates of infiltration and groundwater flow. Organic matter content of soils is one of the most commonly measured component at the CZOs.

For land and atmosphere measurements, all CZOs are using or have plans to use LiDAR and measure wind speed and direction, precipitation and throughfall, and wet and dry deposition.

The measurement of vegetation and microbiota had the least number of measurement categories. All CZOs are or will be measuring the structure and function above and below biomass, and all but one CZO is or have plans to measure microbial composition above and below ground.

For the saturated zone, all CZOs are measuring petrology, mineralogy, elemental composition, and texture of the solid phase and are or will use sensors to measure groundwater potentiometric head in at least some locations. Fewer are using geophysical methods to examine depth to bedrock and only three are or have sampled gas chemistry.

Surface water measurements at CZO were generally less common than soil/vadose zone or saturated zone measurements, with all measuring instantaneous discharge (no mention of continuous

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[6] Knickpoints, lithology, aspect and climate, elevation gradient, land use, and carbon storage and dynamics.

discharge), stream water chemistry, and sediments in at least some locations. Only three locations were examining aquatic biota, either themselves or through partners.

Research Question 5. *Examples of Existing and Ongoing Applied CZO Research at the CZOs*

The Jemez-Santa Catalina CZO has been a leader in identifying and quantifying the societal value of the CZ in a way that can be used to make environmental management decisions and integrate CZ processes. They have expanded the concept of ecosystem services (e.g., provision of drinking water and climate control) to apply to the CZ.[7] A cross-CZO group has formed to examine the application of ecosystem services concepts to the CZ. Research on the effects of wildfires at the Reynolds Creek and Boulder Creek CZOs has begun to produce information that could help local and state-level decision makers, and these efforts are continuing. The Calhoun CZO has discovered that land degradation can be rapid, but recovery is slow. The Eel River CZO has contributed to understanding the controls on stream water quality and linkages with best forestry practices, better predicting how ecosystems will respond to future climates, and improving representations of the CZ in global models. The IML CZO is uniquely positioned to make contributions to applied science because its central hypothesis is that, through human modification, the CZs at their three sites have passed a tipping point, and progress has begun to be made. At the Luquillo CZO, their new understanding of nutrient dynamics and stream quality directly contributes to better models of ecosystem services and an improved understanding of environmental function. The Shale Hills CZO research has contributed to decision making through creating models and examining the effect of climate change on wetlands and water resources, developing a publicly accessible database on water quality in an area with extensive natural gas development, and collaborating with the Forest Service on the relationship between geology and oak regeneration. The Southern Sierra CZO has contributed to the understanding of how drought and fire suppression affect ecosystems and how sustainable forest thinning can improve conditions. Outreach about these activities is of paramount importance to convey to the public how CZ science can be used in decision making at the local, state, regional, and national level.

Quantifying ecosystem services for critical-zone processes could include a ranking of values, assigning per-unit values, or other approaches. Two prime examples of where the social sciences could benefit CZ science include:

- Ecosystem services is probably the most high-profile finding related to identifying the societal value of the CZ. However, how this concept applies to the CZ needs to be described in a more accessible way. As an example: Best practice in communication about ecosystem/CZ services. See: http://www.carangeland.org/images/Ecosystem_Services_Messaging_Needs_Assessment_072512.pdf (created for the Bullitt Foundation by Resource Media)
- The relationship between EEMT [effective energy and mass transfer] and CZ structure and processes is one of the big findings of the first eight years of CZ research, but it also needs to

[7] Critical Zone Services: Expanding Context, Constraints, and Currency beyond Ecosystem Services. Field J.P., Breshears D.D., Law D.J., Villegas J.C., López-Hoffman L., Brooks P.D., Chorover J., Barron-Gafford G.A., Gallery R.E., Litvak M.E., Lybrand R.A., McIntosh J.C., Meixner T., Niu G-Y., Papuga S.A., Pelletier J.D., Rasmussen C.R., and Troch P.A (2015). Vadose Zone Journal 14(1) Abstract available: https://dl.sciencesocieties.org/publications/vzj/abstracts/14/1/vzj2014.10.0142

be described in a more accessible way, with multiple examples, so the significance of the finding can be understood by non-scientists.

Research Question #7. Applied CZO Science – Baseline Evaluations

The importance of using observatories as baselines for catastrophic events (e.g., fires, extreme storms) has been mentioned, but much more could be made of this point in each CZO. The definition of baseline can vary, but in this context it refers to conditions absent impacts or major disturbances that are under investigation. Baseline evaluations can include a series of evaluations of current/existing conditions. Without baseline evaluations, such as those that are ongoing at the CZOs, one can't evaluate the changes to ecosystem function or services that are taking place over time, space, or in response to a "jerk" (fire, storm…) or continuous (climate change) event. One example of how the concept of baseline can be used in applied CZ research is the use of the Shale Hills water quality database to help evaluate whether groundwater quality has been affected by ongoing or future hydraulic fracturing.