Critical Zone Observatory Steering Committee Report
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Prepared by CZO Steering Committee Members

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Background

The national Critical Zone Observatory (CZO) meeting was held in San Juan, Puerto Rico on May 29-June 1, 2012. Hosted by the Luquillo CZO, the meeting included two days of discussions with participation from PIs representing all six sites, plus representatives from the National Science Foundation (NSF) and the Steering Committee, and a day-long field trip to the Luquillo field sites that included a larger group of researchers and graduate students. The three members of the Steering Committee attending and principal authors of this report were L. Derry, M. Firestone, and G. Grant.

Taking stock: where are we now?

The CZO program is at an important juncture as a national scientific program and initiative. The first cohort of sites (Sierra, Boulder, Shale Hills) are finishing their fifth year of funding and have applied to NSF for a one-year non-competitive accomplishment-based renewal, while the second cohort (Luquillo, Jemez/Santa Catalina, and Cristina River) are finishing their third year and have been asked to spend their remaining allocation (total for both years 4 and 5) in year four. These changes were announced in February shortly before the originally scheduled renewal proposals for Cohort 1 sites were due. All sites have been informed that there will be a new open competition for the CZOs, with the solicitation scheduled to be released in FY 12, and proposals due mid-FY 13 with funding for the successful sites to begin in FY14; NSF leadership has indicated that 8 sites will be funded under this solicitation. Moreover, NSF has indicated that they intend to fund a national CZO office, with timing of the solicitation unspecified but likely in the near future.

These recent developments, particularly at a time of overall Federal budget decline, signify a strengthening of NSF's commitment and support of the CZO program. Despite the difficulties and challenges experienced by the Cohort 1 sites as they were forced to change course on short notice, the long-range prospects for the program are quite positive, and reflect optimism and expectations on the part of NSF that the CZOs represent a flagship investment by Earth Sciences (EAR) that will pay-off in important, transformative, and integrated science. The Committee shares this belief, and commends NSF leadership for their ongoing support of the CZO program.

With increased funding comes increased responsibilities, however, and this expansion of the CZO network to 8 sites, plus other related developments, poses new challenges for the network. Our discussions and this report focus primarily on laying out these challenges and our suggestions as to how best to meet them, which the Committee believes will require something more than business as usual.

Fortunately, the CZO program has a set of impressive strengths to draw upon in moving forward. Individual sites express these to varying degrees, but all sites can claim them as legitimate successes of the program to date:

A fundamentally integrated research program that solicits and incorporates the perspectives, techniques, and analytical insights of a wide range of disciplines, including hydrology, geomorphology, biogeochemistry, soil and ecosystem sciences, and microbial biology. It would be hard to find a more vibrant and interactive venue where scientists representing these various disciplines work together and genuinely talk to and learn from each other. The Committee believes that it is this inter- and trans-disciplinary vibrancy that is attracting an ever-expanding global participation in CZO science.

A diversified portfolio of established sites, each of which supports a diversified portfolio of science. As the Committee has commented about in previous reports, unlike other science programs that may be organized around a place or a technique, the CZOs are organized around an idea – the concept of the critical zone as a nexus for physical, chemical, and biological reactions, transformations, and interactions, all of which relate to the capacity to support life and other ecosystem services. Each of the six sites has approached this idea differently, largely as a function of their particular site geographies and contexts, leading to a rich and growing body of knowledge, conceptual and analytical models, and new insights. This combination of idea-based organization and diversified portfolio approach offers a unique and powerful scientific engine for understanding one of, if not the most complex environment on Earth.

An incubator leading to an explosion of first-rate science on critical zone processes. The Committee continues to be impressed by the quantity, complexity, and overall quality of science being conducted at the individual sites. We know so much more about the critical zone than we did a mere five years ago when the program first started. The insights gained are far too numerous to be listed here but the site PIs have collaborated on a "CZO Top 10 " list of achievements and new perspectives that have been the direct result of the program, although these were not available to the Committee at the time this report was written.

A demonstrated capacity on the part of at least some of the sites to balance the demands of an on-going observation and measurement program with the ability to respond quickly to the scientific opportunities posed by events and disturbances. In particular, we commend the Arizona site for moving rapidly to capitalize on the recent wildfire, and the Delaware site for capturing recent floods. This capacity to respond to changing environments was not

an initial goal of the CZO program, but is likely to become a more important component in the future, as discussed below.

A well-equipped and intellectually vibrant training ground for the next generation of Earth scientists. At this and previous meetings, the Committee comes away with the conviction that one of the most important successes to date of the CZO program is that the sites are providing an unparalleled learning, teaching, and research environment for graduate students and junior faculty. Where else can advanced graduate students find such a rich mix of interdisciplinary science, data, research infrastructure, and opportunity to work with top established scientists and each other? Where else can junior faculty leverage established science facilities, and existing data, measurements, and multi-discipline perspectives to jumpstart their research programs? There is a palpable "buzz" among the students who are clearly excited by their opportunity to work at a CZO site, even without the broader context of knowing how unique it is.

The Challenges Ahead

Taken together, these strengths strategically position the CZOs to meet the new challenges and expectations that both NSF and the broader science community have for the program. But the Committee believes that doing so will require more than just continuing to do what the CZO has already been doing well. There are clear signals from NSF that the new solicitation will not just be a renewal for the existing sites, but a refocusing and/or expansion of effort around key themes and foci that, while they are already implicitly a part of the network, but have not been fully developed to date. The Committee is not privy to and thus cannot speak directly to what the "search image" for the new competition is likely to be. Nonetheless, we can identify certain prominent challenges that face the CZO network at this time that need to be addressed regardless of how the solicitation is written. Beyond NSF, these challenges reflect expectations on the part of the larger science community, society at large, and the responsibilities inherent in the luxury of being able to do science at a time of rapid and unprecedented planetary change.

Challenge 1. All sites need to expand development of integrated, comprehensive, and to the extent possible, quantitative conceptual models of how the critical zone functions and evolves at their location.

By conceptual models, we mean more than simple box and arrow diagrams showing linkages, or broad narratives about process couplings. The conceptual model of a site should be a data-driven blueprint that shows how the investigators see their critical zone as constructed and organized. It should be characterized in terms of states, stocks, and fluxes of key constituents, and show relevant process timescales, domains, and feedbacks. It should be possible to clearly map the current and future portfolio of investigations onto the model, and the model should highlight where gaps in understanding lie.

Such models serve multiple purposes. Beyond providing a graphic representation of the site's "mattering map" and scientific plan of attack, they help delineate generalized pathways and themes that can be exported and compared across sites whereby critical

commonalities and differences can be recognized. These conceptual models thus become a means of articulating network outcomes that go beyond site-based results. They establish generalizable frameworks for prediction and modeling and facilitate communication between site researchers and students and with more general audiences.

To further this goal, the Committee recommends that the PIs and NSF plan at least one workshop where different conceptions of the critical zone emerging from the CZO network can be compared and contrasted. This should be more than an AGU session, although a session and perhaps special issue of an appropriate journal could follow such a workshop. The Committee recognizes that all of the sites have developed such conceptual models to some degree, and most PIs necessarily carry them around in their heads. Moreover, the need for such models was clearly recognized in the 2010 paper "Future directions for CZO Science" written by the CZO community; see Goals 1 and 2 for example (http://www. criticalzone. org/CZO-FutureDirectionsReport_v3-1. pdf). But they need to play a far more explicit role in highlighting and explaining the CZO program both to ourselves and others. In other words, they need to be seen as centerpieces of understanding and yardsticks of progress, rather than, as one wag put it, "a set of fuzzy concepts without any math". *The conceptual models should be on our wall!*

Challenge 2. In developing their research portfolios, sites should emphasize studies that specifically leverage the presence of the larger CZO infrastructure.

As noted above, there has been a dramatic increase in CZ studies over the past five years. While this is all to the good, it is a legitimate question to ask how many of these studies could have been done as single PI projects without the major investment in CZOs. Answering this question is tricky, however, because while it's possible to argue that specific research could have conceivably been funded as a sole PI grant, many of the studies currently underway at CZOs simply would not exist without the larger infrastructure to provide context and support. It's unlikely, for example, that a deep drilling project would be funded as a one-off enterprise; attaching this work to a CZO provides a much stronger rationale. Nevertheless, the Committee believes that insufficient attention is being paid to this question of how much added value is being provided by the CZO network. This question is being raised not just by NSF but also by the larger earth science community who see scarce resources concentrated in one program. The CZO investigators need not feel defensive in addressing this issue but point to: 1) evolution of conceptual and analytical models and understanding that could not otherwise be advanced without the overarching CZO framework (as discussed above); 2) advances that are clearly based on synergies from multi-disciplinary lines of attack, long term measurements and datasets, and critical masses of investigators and graduate students; and 3) clear examples of value added by co-located research activities and facilities.

Challenge 3. Sites need to explicitly expand their focus to include observing, modeling, predicting, and explaining environmental change on societally relevant timescales (decadal to centurial).

This was perhaps the clearest message to come from NSF leadership, and it represents a significant but tractable challenge to the CZO network. The broader context was provided by Jun Abrajano (Acting Director of the Division of Earth Sciences [GEO] at NSF), who stated that the ability of NSF to continue to support and grow the CZO network rested in large part on the ability of the network to play a leading role in providing the terrestrial component of the global observation, monitoring, and forecasting infrastructure that is currently dominated by the atmospheric and oceanographic sciences. But as Jun indicated, and the Committee concurs, this challenge goes beyond science institutional politics. There is growing consensus within the greater scientific community that environmental monitoring, modeling, and prediction has to play a much more visible and engaged role in helping to guide public policy and decisions. Two recent publications clearly make this point. In the June 7, 2012 issue of *Nature,* Barnosky and others (2012) state in a paper on global change:

> The plausibility of a planetary-scale 'tipping point' highlights the need to improve biological forecasting by detecting early warning signs of critical transitions on global as well as local scales, and by detecting feedbacks that promote such transitions. It is also necessary to address root causes of how humans are forcing biological changes.

A commentary in the New York Times on June 1, 2012 by Bill Hooke of the American Meteorological Society makes a similar pitch:

> One common challenge for all humanity in the 21st century is managing our threefold relationship with the Earth, as a resource, a victim, and a threat… We can't afford to fly blind into this problematic future. For that reason, Earth observations, science and services, taken together, constitute a critical infrastructure every bit as vital to our well-being as the electrical grid, our communications networks, our sewage systems and our roads and bridges…That infrastructure's ability to meet 21st-century needs is compromised by its near-invisibility to the general public…the lack of a national strategic plan for developing and sustaining the infrastructure and putting it to work for societal benefit…and the limitations of the public-private partnership that has been cobbled together over decades to keep it going.

While the emphasis in the first quotation is on biological monitoring and atmospheric observations in the second, the underlying message applies equally well to CZOs. With the possible exception of some LTER sites, nowhere else in the terrestrial sphere has there been the combined investment in on-going research, infrastructure and high-resolution measurement and modeling, providing an integrated platform to examine the coupling of soil, water, sediment, biogeochemical, ecological, and geomorphic processes that are likely to be in play in any set of plausible future scenarios.

This potentially places CZOs at the forefront of terrestrial environmental monitoring and modeling, which is the case that has been made by NSF. The challenge, however, is that this charge represents a new responsibility on and expectation for the network – one that was not clearly specified in the original solicitation for the current sites, and one that may or may not be an explicit part of the individual site research portfolios. But although the CZO

network was not initially designed to explicitly measure and predict environmental change per se, its capacity to serve as an integrated laboratory for addressing the implications and impacts of environmental change on ecosystem services is not a new concept. Indeed, the aforementioned report on future directions for CZO science recognizes the issue clearly:

> The immediate challenge is to develop a robust predictive ability for how CZ attributes, processes, and outputs will respond to projected climate and land-use changes. This predictive ability must be founded on sufficiently broad knowledge of critical-zone processes to describe how the varied climatic and geologic factors that distinguish different regions interact, and require advances in measurement, theory and modeling. http://www. criticalzone. org/CZO-FutureDirectionsReport_v3-1. pdf

In other words, the goal for the CZOs of incorporating observation and modeling of processes relevant to environmental change and human timescales and decisions is already collectively acknowledged by both the sites and the funders. The framework and justification are already in place. From the Committee's perspective what is less clear is how the sites are orienting their research programs towards this goal. The research that was presented was by and large first rate, but the connections between this work and the "so what" question went largely unexplored. This has to change – and it's clear that the next solicitation for the CZOs will have this charge of addressing the larger societal relevance of CZO research as an explicit component.

The connection should not be that difficult to make, but it will require focus and discussion, both within and among sites. A number of key research questions underlying projects that are already underway at the sites seem well poised to nucleate that discussion and provide clear examples of where and how the CZO network can contribute. These include:

1. How are the volumes, timing, and quality of streamflow due to changing climate and land use likely to change in the future? What critical zone processes are responsible for these changes, where are the changes likely to be most pronounced, and what landscapes are relatively insensitive to change?
2. What controls the development of water stress in vegetation? How does the basic architecture of the critical zone affect the temporal and spatial dimensions of plant-available water, and how will changing climate and land use affect water stress in the future. Under what circumstances does water stress lead to cascading disturbances of drought, fire, mortality, etc?
3. How might fundamental weathering regimes shift in the future, including effects of changing climate and land use on the integrated weathering environment of soil, water, microbial populations, and biogeochemistry? What are the implications of these shifts towards release of carbon and other greenhouse gases? To what extent will water chemistry of rivers change as a result of changing weathering regimes?

Research to address these and other relevant questions is already well underway at the various sites, and linkages with larger issues are beginning to be made. Nevertheless the Committee believes that more attention needs to be paid to making these linkages explicit,

developing models that explore the environmental implications of alternative future scenarios, and making the results of this research available to a much broader cross-section of the population, not just the immediate science community.

Challenge 4. The individual sites and network as a whole needs to proactively develop and extend their capacity to play well with others

The CZO Network represents a potentially invaluable resource for the scientific community as a group of linked, instrumented and well-documented study sites. It is possible to envision a growing spectrum of studies that take advantage of the CZO infrastructure and science, carried out by both the core CZO investigators and by new investigators outside the current CZO network. We also look forward to more studies across the CZO network, looking at commonalities and differences among the different sites. The scale of investment by NSF, relative to the traditional core programs in the related disciplines, would seem to anticipate broader community involvement and cross-site science. An important but complex question is how this potential can be realized without unduly disrupting the ongoing research programs at the CZOs. Keeping in mind that this will be a highly adaptive and evolutionary process, there are a few suggestions we can make to help facilitate broader community involvement and the development of network-level science.

1. The availability and accessibility of data from the network sites on the web is a key issue. As discussed at the meeting, there remain significant challenges in developing the necessary cyberinfrastructure to capture data from the CZOs and make it available in a flexible, user-friendly way. At present, access to basic data from the CZOs remains incomplete, and the interface for each site differs. These are perfectly understandable issues in light if the recent evolution of the program, but should be priorities for the future. A common format for most data, and a common interface and set of search tools will allow scientists and students from outside the network to find, organize and understand the basic data streams that the CZO sites generate. This in turn will allow new users to generate questions and ultimately testable hypotheses in areas that were not anticipated by the original science teams.
2. We believe that NSF would send an important message to the community in clearly identifying funding for research that interfaces with the CZO network. Current policy appears to be that the NSF core programs will consider CZO-related research proposals, but that they will essentially be treated as any other proposal to the program (or at least there is no public statement otherwise). Given the low success and funding rates in some of those programs, this may not be sending the right message. A targeted program, even of modest size, or perhaps a set of "matching funds" if a proposal is well reviewed by the core programs, would emphasize the Foundation's commitment to broadening participation in the CZO network.
3. Cross-site science appears to be attracting more attention, as the individual sites become established and the possibilities more apparent. As in the past, the Committee wonders if a dedicated post-doctoral program to develop cross-site science would be a useful tool. The PIs are heavily engaged in their respective sites and so finding time to

develop cross-site science is challenging for them. Outside scientists or postdocs could be effective at "spinning up" studies that compare processes at different sites or ask network-wide questions.

We view the continuing development of shared measurement and data protocols to be a positive step, and applaud the PIs for their work on these issues. It is clear that there are a number of measurement and reporting conventions that make sense, but we would not want to see (nor do we expect) over-emphasis on common data types because this could have the potential to limit the development of new approaches. A one-size-fits-all approach would not be a good idea, but where common protocols make sense we encourage them.

Leadership and planning for succession

Since the initiation of the program, the leadership of the CZOs has been responsive to changing needs. However as the character of the CZOs evolves and as the demands placed on the CZOs changes, it may be necessary for the composition of the leadership teams to adjust. The Steering Committee recommends that the two PIs leading each CZO represent distinctly different disciplinary areas. This alone implements some minimal disciplinary breadth of perspective. It may also be useful for the PI composition to include some aspect of diversity (career age, gender, ethnicity as possible examples).

While project continuity and memory requires some consistency in the leadership team, these project characteristics can also be facilitated by planning ahead for leadership succession.

Criteria for future CZO sites

Future decisions on funding of CZO projects will likely consider geographical location, parent material, and climate. We suggest that importance also be placed on the character and diversity of processes represented in the science plans proposed. In addition, the value of gradients (physical, chemical, and biological), needs to be appreciated; such gradients provide a potentially-important approach to identifying major drivers as well as enhancing possibilities for extrapolation to other locations. The CZO portfolio also needs to include a range of human impacts and disturbance regimes. Understanding and quantifying the roles of these "external drivers" needs to part of the CZO product.

Communication issues

Communication is multidirectional. We heard substantial frustration from several PIs as to the changing NSF plans for future funding. While this frustration is understandable, the reasons for the changing NSF plans were compelling and in fact additional "bridge" funding was supplied. It may be, however, that uncertainty and evolving conditions could have been better communicated to the PIs.

In the past, the Steering Committee has been contacted primarily when something was explicitly needed. Potentially useful information, however, such as the results of the CZO program review, was not communicated to the Committee. In the end, the Committee

concluded that this cloud had a silver lining; the absence of information allowed the Steering Committee to craft its opinion and recommendations entirely independently to those of the NSF programmatic review committee.

Role of the Steering Committee

We think the Steering Committee has played and can continue to play a useful role for the CZO program. We see our role as partly advisory, providing an "informed outsider's" view of the program. We have tried to represent the perspectives of the wider surface process/biogeochemistry community on some occasions, and conversely find ourselves advocating for the program with other scientists who may not know very much about it. Secondly, we think we can help with communication between the CZO PIs and students and NSF management. We develop a sense of each group's perspective, often in informal interactions, and have tried to judiciously represent those views to the other groups in ways that might not be available in the formal interactions between NSF and the PIs. We hope and believe this has been helpful to all concerned. The chance to be involved to some degree in the CZO program and to stay informed of the many exciting developments is the major reward for the Steering Committee members, in addition to providing a service to the CZ scientific community. If that service as an outside voice and as a facilitator of communication is considered valuable by NSF and the PIs then we believe the Steering Committee can continue to play a useful role in the program.

CZO National Office

A concept discussed at the meeting was the role of a potential National CZO Office. We did not discuss this extensively amongst ourselves, but had a few thoughts that to some degree echo those in the broader group discussion. A National Office has the potential to increase visibility for the program, but in the long run we feel that visibility will be primarily garnered through the development of exciting scientific results. A National Office could play a useful role in coordinating and fostering common data archiving tools and web access to data and information across the network. It may also be helpful with certain kinds of outreach activities, although cannot be a replacement for the site-based outreach that a number of the CZOs currently are engaged in. For example, the development of K-12 curricular materials or teacher background information about the concept of the Critical Zone might be something that a National Office could enable.

Graduate Education

The members of the steering committee have been impressed by the strength and engagement of the graduate students working under the CZO umbrella. The students with whom we spoke during the field component of this review expressed major enthusiasm for the value of their attendance at the "all-hands" meeting held last year at BioSphere 2. While the inclusion of graduate students in the bi-yearly "all-hands" meeting is great, additional opportunities for cross-site interaction and exchange are very important. Steps are being taken toward improving on-line opportunities for interaction among graduate (post doctoral and undergraduate should be included) students. A variety of additional

interaction opportunities should be considered. “Cocktail hour”/ Beer fests/ Lunches at major national meetings where a number of students will be in attendance, could enhance communication, interaction and collaborations across sites. The value of an off-year, all CZO, all grad student meeting may also be substantial.

In addition to cross-CZO student interactions, a bit more attention should be paid to interactions of students within CZO sites, and between CZO and other co-located sites, such as LTERs. These interactions provide an important sense of common mission as well as additional hands for field campaigns. Perhaps more importantly, these interactions serve as a foundation for the cross disciplinary education of the students. We have found that the graduate students working on CZO projects are generally becoming knowledgeable and conversant in a range of disciplines. Much of this understanding comes from student-student exchange. While each of these students will presumably acquire the deep disciplinary expertise necessary for them to contribute to their respective fields, the cross-disciplinary knowledge and experience gained through their CZO interactions, should provide a strong and necessary foundation for future research addressing complex, multifaceted questions.

There are multiple possible benefits of graduate student nucleation of cross-CZO thematic groups; with some minimal encouragement and direction, students can initiate and organize the planned thematic groups. All grad students need to be informed of these possible themes. These groups may primarily operate on-line. PIs and other CZO researchers should be encouraged to participate, but the activation energy for implementation and the vitality of these groups should come from the graduate and post doctoral students. Group discussions can occur at national meetings.

A basic level of education in field safety is essential for all CZO personnel but particularly students. Such education needs to be site-specific as potential safety issues in the Rocky Mountains differ from those in Puerto Rico. CZOs may be able to leverage existing programs; for example, the Luquillo site might be able to tap-into Forest Service programs designed to accomplish similar goals.

Luquillo site review

The Committee agreed that the Luquillo CZO (LCZO) has come a long way in the past 2 years. The presentations of CZO-associated research were quite interesting and generally impressive. The disciplines represented were appropriately broad (geological weathering, hydrology by isotopes, atmospheric deposition, control of watershed export and soil forming factors, hydrology of storm pulses, sediment transport, history of sea level change and uplift on coastal character, SOM quality, quantity, and microbiology, redox control of C-cycling, lithological basis of current landscape and ecosystem patterns). Many of the individual projects represented important, cutting edge work; they were generally also free-standing with little connection to the LTER project "up the road." For some of these projects there was little to be gained by connection/interaction with the project next door; but for

others, interaction might enrich and deepen the science. The fact that CZO researchers themselves were surprised and impressed by what they learned on the field trip suggests that a bit more within site communication could substantially further the goal of cross-disciplinarity and genuinely further the research goals of the LCZO.

The LCZO needs to consider how it can best leverage LTER data sets, scientific infrastructure, and personnel, particularly graduate students. Clearly the identity of the Luquillo CZO needs to remain distinct from that of the Luquillo LTER. That said, there is a tremendous potential for cross disciplinary exchange between the CZO and the LTER. During field season, when many grad students are in residence, joint LTER-CZO grad student events might begin the building of a broader grad student cohort at Luquillo. The CZO-based Luquillo grad students seemed to have virtually no interaction with LTER-associated students and articulated belief that the CZO and LTER students constituted "different communities of practice". Grad students from U Penn dominate the CZO grad student cohort. In fact the coincidence of the LCZO with the Penn cohort of students may in itself provide some of the resistance to crossing the great CZO-LTER divide.

References:

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