Report of the Steering Committee
Critical Zone Observatories
2010 Annual Meeting

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Members of the Critical Zone Observatory (CZO) Steering Committee met with CZO participants (PIs and associated senior personnel, students, post-doctoral associates), representatives from programs (USGS, SoilTREC, SDSC Center, etc.) cooperating with the CZO effort, and representatives of the National Science Foundation, during the Annual CZO Meeting in Boulder, Colorado on 13-15 September 2010. Below is the report from the Committee containing its assessment and recommendations based on information presented during the Annual Meeting, discussions with meeting participants, and ancillary material provided to the Committee.

This report focuses first on the questions posed to the Committee by the CZO PIs prior to the Annual Meeting. We then address several key topics that emerged during the Annual Meeting, followed by a few brief reactions regarding individual CZO sites.

Questions to Steering Committee
Committee members felt that questions (1) and (4) are closely related, so we address these questions together. In addition, here we address question (3) in general terms, but focus on the specific topic of engaging biology and ecology in the CZO effort in a separate section below.

> **Question (1):** In what ways are the CZOs currently having impact on earth surface science, and how can the impact be maximized? **Question (4):** What directions stand out as innovative and exciting in CZO research to date?

Several examples can be highlighted as representing how the CZO effort is either currently impacting, or is poised to steer, scientific thinking.

The overarching idea of a "Reactor on a Slope" represents an important conceptual advance, as it emphasizes how extant physical and biochemical conditions at any position on a hillslope may be strongly influenced by integrated effects of transport and reaction upslope, subject to effects of changing boundary conditions. This in turn provides a framework for systematically examining, theoretically and empirically, the coupled physical-chemical-biological processes that yield characteristic catena structures, including the biogeochemical preconditioning of regolith material in setting "soil production" and particulate transport — therein providing a natural connection with modeling of landscape dynamics. We recognize that this effort is not aimed just at hillslopes, but rather that the CZO effort also is aimed at generalizing the idea of the "reactor" to catchment (and possibly larger) scales.

In relation to this "reactor" idea, the Committee applauds an increasing CZO effort to adopt the

formalism provided by transport-reaction modeling (involving both fluid and particulate phases). This includes work at relatively short timescales, where modeling is understandably centered on hydrological conditions and behavior, and at longer geomorphic timescales, where modeling is necessarily at a more synthesis level, but nonetheless faithful to essentials of conservation, transport and reaction. This CZO effort represents a framework — a common language — for describing landscape/CZ dynamics that moves beyond specific locations. An important measure of the impact of this specific CZO effort will be the extent to which the larger CZ community picks up on and adopts this common language. Moreover, one of the interesting challenges presented by CZOs is framing the science in terms common to both the biological and physical sciences. For example, many physical processes can be scaled using dimensionless numbers, thereby allowing comparisons among disparate systems and settings, as well as assessments of the relative importance of operative processes. Such dimensionless numbers also are used in biological and ecological research focused on coupled transport and reaction, for example, biochemical processing and spiraling in porous-media flows and in streams.

Another important, emerging theme of the CZO effort is that the time (duration) over which both fluids and particulates reside in the "reactor" and undergo mixing (in situ or during transport) may strongly influence weathering processes and their spatial variations; that transit time and mixing are fundamentally involved in the types and rates of reactions over hillslope/catchment scales. Also of significance is the related idea of using transit time ("age") and mixing of waters and their constituents to constrain hydrological modeling efforts. This work merits elaboration, perhaps as a cross-cutting theme across CZO sites.

The Committee notes that key questions concerning the processing and cycling of carbon, including its relation to weathering processes, are being pursued at most if not all of the CZO sites. The topic of carbon processing and cycling *per se* is broad, represented by a wealth of research across several fields. The CZO effort represents an opportunity to contribute to this body of research specifically through the lenses of CZ processes coupled with landscape dynamics, with both basic and applied relevance to weathering, carbon transport and sequestration, issues of water quality, and responses of carbon processing/cycling to changing climate and land use.

Another key emerging topic of broad scientific interest is the rigorous elaboration of the "Janus-like" behavior of water in the landscape, where the presence/absence of water is a first-order control on the rates of biophysical reactions in the landscape/reactor, while at the same time the chemistry of the water is controlled by those reactions. The double-edged role of water as both driver and responder recasts the fluxes of water in an entirely new light. New techniques to sample water chemistry across a much wider range of chemical species is likely to yield surprising insights into how water moves through, transforms, and is transformed by the CZ.

The explicit coupling of weathering, geomorphic processes, topography, and landscape evolution represents a significant new avenue of work that is not currently represented (in its entirety) in current landscape evolution models. Work to understand and measure the strength of this coupling has the potential to open the door to some very different and exciting stories of the complexity and feedbacks in the development of landscape form.

The Committee was encouraged by the efforts of CZO scientists to start to synthesize patterns across the CZOs and other sites. In particular, the proposed framework of examining patterns across

climate, lithology and disturbance space seems to be an effective initial approach. This synthesis work provides justification for the investment by NSF in a network of sites and could result in transformational science. The Committee encourages the CZO scientists to continue this exciting work.

The Committee suggests that the items outlined above constitute strengths of the CZO effort that the PIs should consider building on. That said, the Committee wishes also to turn the questions of this section, in slightly different form, back to the PIs. Namely, what are the unifying ideas/hypotheses/theories that are emerging from the CZO effort which, when fully elaborated, will steer the course of thinking in Earth surface/CZ science? What will it take, in terms of collective focus and effort, to fully understand and articulate the ingredients and implications of these unifying ideas? In effect, the Committee is challenging the CZO effort to move beyond a phase of posing questions (although certainly compelling questions will continue to arise, notably, for example, when the LIDAR data become available) to a point of elaborating unifying testable hypotheses or "theories" of CZ processes/dynamics.

> **Question (2):** How should we prioritize efforts between science within a site and integrating science across sites? Infrastructure development and model development? Integrated data management and outreach?

The Steering Committee does not believe it is appropriate to recommend a priority for efforts of the CZOs. However, the Committee does recommend a frank discussion among the CZO leadership on this topic (see section below on Overarching Objectives of CZO Network). For the long-term success of the CZO as individual sites and as a network, each site needs a substantive commitment of resources and time in all of these areas. Moreover the Committee believes it is in the CZOs best interest if the level of commitment across these areas is similar among the sites.

The balance between efforts within individual sites versus integration across sites must go with the maturity of the sites, including the stage of establishing needed infrastructures at sites, and the stage of accessibility of common data sets. This balance might be guided by cross-site hypothesis development, and the status of overarching objectives in moving toward the idea of a CZO network. It may be that, in pursuing this network idea, some steering or focusing of efforts occurs at individual sites. The Committee certainly applauds the development of cross-site integration; but not at the expense of particularly compelling science at individual sites.

The Committee notes several highlights.

- Kudos for the impressive, collective effort (with Mark Williams' leadership) given to issues of data management, development of a common vocabulary, increasing the accessibility of data in usable forms, etc.; the Committee fully appreciates that this is a challenging, continuing "work in progress" as key issues are sorted.

- Kudos for the efforts to secure the LIDAR flyovers; this is a fantastic opportunity that will most certainly lead to interesting hypotheses/analyses when the processed data become available.

- The Committee views efforts to explore ideas and opportunities for adopting technology from each other as positive (which may be particularly important for the newer CZO sites); consider

an IRIS model of transportable (also see section below on Common Measurements and Technology).

Question (3): How can we better engage the science community in using the resources of the CZOs?

The Committee believes that the CZOs are doing a good job engaging the broader earth science community into their research. The best way to interact with the broader science community is to make CZO data available as soon as possible in a readily accessible manner and encourage its use. The CZOs are in the process of doing this through their planned common information management program. Another mechanism for encouraging broader use of the CZOs might be for NSF program managers to state that proposals that piggyback on CZO sites, data, and/or facilities "are especially welcome" to take advantage of the existing investment and leverage resources. CZO scientists are also actively presenting their research findings at professional meetings and publishing their findings in the peer-reviewed literature. The CZO scientists should make sure that they acknowledge the NSF CZO program in their presentations and publications. The Committee believes that the CZOs could and should do a better job engaging biologists to work at CZO sites and in the CZO research program. Suggestions for engaging biologists in CZO work are discussed below.

Key mechanisms of engagement with the broader community include the interactions with the SoilTREC effort, working group efforts, and the efforts to establish a "CZ science" identity through engagement and training of students and post-docs in CZO research.

Overarching Objectives of CZO Network

The committee fully recognizes that individual sites were initially funded based on the quality and anticipated success of their site-based research programs. Moving towards a CZO network of sites has to occur within the constraints of the established site science efforts; from our conversations, it is clear that NSF leadership understands and supports this direction as well. But it is also clear that the long-term success of the CZO program will rest on both rigorous place-based science and exciting developments that involve multiple (but not necessarily all) sites. It is not too early to begin to explore how to best foster the evolution of a CZO network.

In the Committee's view, this can occur in at least three distinct arenas. The first is multi-site studies that use common approaches, methods, models, measurements, etc. to examine common themes and develop lucrative "compare and contrast" analyses that open the door to observations and insights that could not be obtained if the work were restricted to a single site. An example of this work is the effort being led by Sue Brantley and others to examine weathering processes across a range of geologic and edaphic gradients. A second arena is the effort to establish common measurement protocols, platforms, and instrumentation to support acquisition of cross-site data bases in order to facilitate future inter-site studies, even when the questions have not yet been formulated. Multi-site acquisitions of flux towers, LIDAR, etc. fall into this category.

A third arena where a CZO network can begin to evolve, related but distinct from the first two, is development of common conceptual and theoretical frameworks — a common language if you will — that addresses the heart of CZO science. Such frameworks move beyond individual or even multi-site studies to a higher level of synthesis and theory. The first step towards developing this common language is for sites to begin to formulate clear conceptual models that capture their

understanding of how their sites "work": how the hydrologic plumbing systems, geochemical systems, geomorphic processes and landforms, ecological systems and mechanisms, and soil development are all coupled together to give rise to complex system behaviors. This sort of site vision, using concepts that can be shared by other sites, needs to be the organizing principle around which individual studies are based and hung. It should be the "cartoon" that is presented at the start of CZO-related talks, and should provide the basis for the more rigorous modeling and theoretical work that ties all the pieces together. We see some beginnings of this in individual sites, but the concept overall has not been fully embraced. It should be.

Engaging Biology and Ecology in the CZO Effort

The Steering Committee discussed the importance of increasing the presence of biology in the research portfolios of the CZOs. The committee urges the researchers at each CZO to consider what research questions (coming under a biology rubric) are most central and relevant to the work currently ongoing as well as to the research anticipated in future years. As specific questions or hypotheses are identified, it may be useful to post these questions under an "Outstanding Questions" section of each CZO's website. Identification of interesting and relevant questions may be greatly facilitated by discussions with possible biological collaborators and more broadly by presentations of CZO research plans at meetings of ecologists and biologists. The CZO network needs to increase awareness of their research program generally among members of the relevant biological communities by oral and poster presentations at ESA, AGU, ASM, and ASLO. There was concern among members of the steering committee that biologists in general were almost totally unaware of this research initiative.

As interest is piqued among biologists to participate or collaborate with CZOs, funding streams for such research must be cultivated. NSF-supported biological research within the Division of Environmental Biology (DEB) may provide a receptive venue. Within this Division, two programs, Ecosystem Science and Population and Community Ecology may be the more likely programs to fund research that is located at a CZO cite and leverages CZO data and resources. Two of the CZOs have some overlap with Long Term Ecological Research (LTER) sites. Members of the steering committee were interested in whether synergisms were occurring and more specifically if the research capabilities of these sites were enhanced by possible interactions of CZO-LTER researchers or sharing of infrastructural resources.

NSF provides support for two other research networks or centers, these are LTER and NEON. The steering committee believes that coordination among these programs and CZO may be facilitated by awareness and conversation among NSF program managers. Catalysis of conversation and coordination among the three programs may be valuable to each and all of the programs.

Upcoming Program Review

Given that the three initial CZOs are beginning their fourth year of a five year project, it is time to think about the next steps for the program. Both a review of the program to date and a mechanism to extend the program are needed, as discussed at the Annual Meeting. NSF program officers indicated a preference for a Reverse Site Visit to be held at NSF this spring. We believe that a review and evaluation of the overall program is the most important goal of such a meeting, as opposed to a primary focus on the accomplishments of individual site-based projects. While the later are obviously very important, the overall success of the program should be judged on how the establishment of a network of Critical Zone observatories has and can continue to advance the

science. Three years is also a short time frame over which to evaluate the success of individual sites, since the need to establish infrastucture of various kinds (data collection, data management, site management) has clearly and quite understandably consumed a considerable amount of time and effort on the part of the PIs and their colleagues. Intriguing research results are clearly beginning to be demonstrated, but the time frame for such complex site based projects remains short.

While the same issues are relevant to a wider program review, the Committee feels that a reasonable assessment can be made of the effectiveness and potential for the CZO program as a whole to influence the science of the Critical Zone. There are several criteria that we suggest would be relevant to such an evaluation.

- Does the integration of multiple disciplines at a site provide opportunities to advance the science in ways that are fundamentally different from a set of individual "single PI" projects?

- Does the development of the CZO network provide a platform for research that can advance the science in new and innovative ways, again different from that which might be achieved by a series of smaller independent projects?

- Are the CZOs acting as catalysts for the development of new observing and/or measurement techniques, new data integration tools, and/or new novel modes of interdisciplinary research?

- Are the CZOs enabling researchers from outside the original core group to use the facilities in ways beyond those described in the original proposals?

- Can a CZO network grow and adapt to new questions involving new researchers?

- How much progress is being made on the complex task of data management and data access?

If the CZO program is judged to have particular merit, the question of how to sustain it becomes key. A new solicitation should provide a means for continued support of CZO sites that have been effective and provide a strong rationale for how continued support will enable innovative science. It should also provide a means for attracting proposals for additional CZO sites that can extent the range of environments and processes studied in this integrative framework. Clearly the types of proposals expected from an existing CZO and from a potentially new one are different and must be evaluated differently.

Potential new CZOs should be encouraged to take advantage of the experience of the existing CZOs in developing infrastructure and to use the emerging data management systems now under development. While the initial RFP did not include any mention of integration with other sites, this might be an optional part of a new RFP. However, requiring an explicit plan of cross-site work may place an undue burden on new teams.

The initial RFP (NSF 06-588) explicitly required CZOs to focus on a single watershed. In practice the existing JSC project has already branched out to multiple, widely separated sites, and there seems little scientific basis for such a restriction. However, the scientific justification for including multiple watersheds and/or gradients within a CZO framework should be clearly articulated in proposals that choose this type of site design.

An examination of budgets and expenditures may help program managers to establish realistic levels of funding for continuing CZOs versus those that are new, as there are at least some significant costs incurred in establishing a site that will not be recurring. However, the committee feels that it is important that continuing CZOs have the resources to do more than simply maintain facilities and operations, and should be able to extend or initiate new science-driven projects. While more sites may well be desirable, each site must be funded at levels that can realistically support the ambitious goals of this program, and it is important that resources not be spread too thinly. If NSF chooses a pre-proposal format, followed by a full proposal from successful initial submissions, it may be worth having a virtual workshop so that proposers can learn from some of the experience of existing CZOs.

Common Measurements and Technology

If the CZO has interest in evolving into a network rather than a collection of individual sites, cross-site analysis and syntheses will be an important metric of the success and impact of the overall research program. CZO scientists appear to have done considerable thinking and planning about how to advance the program as a network. The CZO meeting provided many examples of this pre-Network thinking. The newer sites clearly have been interacting closely with the older sites to learn from the experiences of the older sites. Some exciting cross-site initiatives, such as the acquisition of LIDAR data and developing a common information management system are underway. The Steering Committee was also pleased to learn about the CZO committee on large infrastructure. This represents proactive thinking on what equipment and activities are needed to advance the sites as a network. The Steering Committee encourages this group to think about the cross-site research questions that would drive this acquisition of major equipment. Any one of these initiatives would represent a large expenditure of funds for the NSF. The Committee would want to see an investment in research infrastructure that would allow the sites so work more effectively together as a network and would also benefit the broader earth sciences community.

The Steering Committee believes that if the CZO wants to evolve into a network, it will be essential that key measurements are made using standard methodologies across all sites. A suite of common measurements could provide a baseline of data and observations that would allow for meaningful cross-site analysis and network synthesis. Without common measurements using standard procedures, sophisticated cross-site analysis will not be possible. Embarking in the direction of common measurements is a big step for the CZO. The CZO should consider such an initiative carefully. There is some great individual research at each of the CZOs. Each site has its own distinct characteristics and strengths. The Steering Committee believes it is important to maintain individual site-based research. However, what makes the CZO distinctive from individual site research is the potential for insights from cross-site research and synthesis. If this is a direction that the CZO wants to evolve, they might consider developing a suite of "minimum common measurements". These common measurements should be based on standard methods that would be accepted at all sites. The common measurements to be made should be decided while considering the cross-site questions that the CZO scientists have. It may make sense to develop these common measurements along themes that occur across the CZOs, such as climate; energy, water and material budgets; carbon sequestration and transformations; and rates of soil formation, weathering and denudation.

Suggestions for Future Interaction with the Steering Committee at Annual CZO Meetings

The Steering Committee was generally pleased with the information obtained at the annual meeting.

The presentations were generally high quality and stimulated much discussion and thought. The Steering Committee commends the CZO scientists and particularly the scientists from Boulder in putting together a good program. The Steering Committee noted that the focused presentations given on Wednesday to be very effective. The Steering Committee found the cross-site presentations on LIDAR, IM and large infrastructure to be very useful in understanding some of the initial discussion and thinking on network activities. The Steering Committee in particular would like to thank the CZO scientists from Boulder in a very successful field trip. The Committee was pleased to see presentations and participation from several post-docs and graduate students.

The Steering Committee had a few suggestions, however, for future meetings. The Committee understanding of site-based research could have been improved if the site presentations included background information on the overaching hypothesis, conceptual model, or theme for the site; some specific research hypotheses or questions; and information on project organization and personnel. This information was provided in a few of the site presentations, but many failed to include this basic background information. It would be helpful for the Steering Committee to have copies of slides used in presentations; this would facilitate the ability of Committee members to make specific comments on aspects of the CZO review. In addition, the Steering Committee would benefit from a separate session with students and post-doctoral associates. (Note students and post-docs might benefit from a session with the Committee.) The posters could have received more attention if they had been posted for the entire meeting in a large room adjacent to the meeting room where the coffee breaks and lunches took place, instead of at the fieldtrip and banquet site where they were only up for a few hours.

Reactions and Recommendations Regarding Individual CZO Sites

Southern Sierra

* Strong emphasis on climate dynamics. This is an important and obvious research focus for the Sierra site.

* Interesting work on records of tree-water use, water storage, variations in sources of moisture. Do trees do hydraulic lifting/pumping? Relation to under-story?

* The idea that litter decomposition might not depend strongly on aspect/moisture related to snow melt timing merits elaboration.

* The idea of preferential flow giving nutrient hotspots, unrelated to overlying O horizon (thus involving lateral flow, where timing also is important) also merits elaboration.

Shale Hills

* Very impressive diverse array of integrated research at the site addressing issues of preferential flow, hydrologic residence time, plant-soil interactions and weathering mechanisms

* Overarching objective clearly articulated: origin/evolution of regolith, predicting it's "function" with feedbacks; systematic attention to: geomorphology (significance of tree-throw, use of Lidar and cosmogenics); soil and weathering (weathering model with elements of residence time, transport); biogeochemistry (CO_2, soil respiration); geophysics (hydrological conditions, fractures are key in shale); hydrology and climate (including stable isotopes, precipitation chemistry); ecology

(vegetation structure/dynamics in relation to hydrology); hydropedology (focusing on soil moisture, preferential flow)

* Significant outreach; STEM/REU educational component through research.

Jemez/Santa Catalina

* Interesting synthesis and cross site analysis being conducted. Very much enjoyed the presentations from Jemez/Santa Catalina.

* For the sampling across elevation/precipitation/geology gradients to examine energy/water budget, what are the specific hypotheses guiding site selection, measurements?

* That DOM is a "driver" in releasing metal (rare earths) merits elaboration.

* Good sample of grad/undergrad involvement.

Christina River

* Strong focus on carbon transformations and the role of organic carbon in critical zone processes. This is an important and relevant research focus. Also good blend of applied field and basic laboratory studies.

* Clear overarching hypotheses and objectives regarding weathering/erosion controls on complexation, sampling across six sites ("all" land uses, including "natural" plus lowland "outflow" sites (with sediment sampling records) along Brandywine.

* Concerning development of low-cost high-quality sensors (particularly geochemical), NSF should consider giving special funding to develop this, as the need is far beyond the CZO; this is in line with the idea of opportunistic funding presented last year

* The idea of bringing sensor collected information to classroom is nice touch.

Luquillo

* The Committee was somewhat disappointed in the level of work presented. The Committee noted no poster presentations nor science talks from this site.

* Conceptual setup is similar to Jemez, considering atmospheric inputs, CZ dynamics, output through flows/sediment

* Current effort centered on sampling design, for guiding soil measurements in support of hypotheses regarding carbon, elevation, precipitation effects in conjunction with geology; indicated attention to catena structure. At what scale(s)? There may be merit in approaching this via the conceptual/modeling framework outlined above concerning the "Reactor on a Slope".

Boulder Creek

* Very impressive presentation of the snow and nitrogen cycling study by Eve Hinckley. The study does a good job of embracing the many of the diverse components of critical zone research.

* Conceptual model clear: that critical zone reactor evolution is controlled at lowest order by denudation rate (where understanding the long term history is a key part of the background for process work at smaller scales).

* Significant progress in establishing environmental sensors; soil moisture, temp, etc.

* Regarding spatial controls on nutrient processing: What are the overarching hypotheses?

* Notable outreach/education activities: Science Discovery program, CU; Keck Project (college level)