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EC SoilTrEC Project and NSF Critical Zone Observatory Programme

Design of Global Environmental Gradient Experiments using International Networks of Critical Zone Observatories

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EXECUTIVE SUMMARY

Earth's Critical Zone (CZ), the thin outer veneer of our planet from the tops of the tree canopy to the bottom of our drinking water aquifers that supports almost all human activity, is experiencing ever-increasing pressure from growth in human population and wealth. Within the next 4 decades, demand for food and fuel is expected to double along with a more than 50% increase in demand for clean water. Understanding, predicting and managing intensification of land use and associated economic services, while mitigating and adapting to rapid climate change, is now one of the most pressing societal challenges of the 21st century. These challenges were addressed in an international workshop of CZ scientists, convened November 9th-11th, 2011 at the University of Delaware, USA. This workshop report outlines the science advances that will be necessary, and documents the links between basic science advances in Earth surface processes and the global sustainability agenda. The overarching hypothesis is that accelerating changes in land use and climate are forcing rapid and profound changes in the continental surface that require an unprecedented intensity and scale of scientific observation and new knowledge to guide intervention. Six priority science questions are identified.

Long-Term Processes and Impacts

1. How has the geological evolution of the CZ established ecosystem function and its sustainability?
2. How do molecular-scale interactions dictate processes in soils and underlying rock, and influence the development of watersheds and aquifers as functional geophysical units?
3. How can theory and data be combined from molecular- to global- scales in order to interpret past transformations of Earth's surface and forecast CZ evolution and its planetary impact?

Short-Term Processes and Impacts

4. What controls the resilience, response and recovery of the CZ to perturbations such as climate and land use changes, and how can this be quantified through observations and predicted through mathematical modelling?
5. How can sensing and monitoring technology, e/cyber-infrastructure and modelling methods be integrated to enable the simulation of essential terrestrial variables and forecasting for water supplies, food production, biodiversity and other major benefits for humankind?
6. How can theory, data and mathematical models from the natural- and social- sciences be integrated to simulate, value, and manage Critical Zone goods and services?

Critical Zone Observatories (CZOs) advance new knowledge needed to support the sustainable management of the CZ. CZOs act as scientific focal points to define major research questions and hypotheses and draw together the critical mass of disciplines and talent to deliver major advances quickly. This design includes international networks of CZOs located along global gradients of environmental change; e.g. in land use and climate. Some common features of CZOs are a wide range of multidisciplinary expertise that is concentrated in order to advance solutions to a specific challenge; a focus on process studies that are hypothesis driven; and a combination of empirical observation at multiple scales with mathematical modelling and simulation. European CZOs are driving forward integration with social sciences and policy, and development of decision support tools for policy and management intervention. USA CZOs are focussed more strongly on advances in data acquisition methods and basic science research. Necessary steps to increase integration between these and additional CZ science agendas worldwide include increased international cooperation between funding agencies, an enhanced directory of current and proposed CZOs, wide international dissemination to a greater array of CZ experts, broad scientific access and contribution to CZO sites and data, recruitment of additional CZOs for research along global gradients, and a prototype web service to link national geospatial data, numerical models and research data.

Earth's Critical Zone and Global Sustainability

Earth's Critical Zone (CZ), a phrase suggested by the National Research Council (2001), is the thin veneer of our planet from the top of the tree canopy to the bottom of drinking water aquifers, upon which humanity is utterly dependent for life support. The Millennium Ecosystem Assessment (2005) defines the vital global economic services arising from Critical Zone processes (see Text Box 1), and the expanding threats to these services worldwide. A projected human population increase to 9 billion by 2050 together with enhanced living standards is expected to double the demand for food and fuel and increase the total requirement for clean drinking water by over 50%. These expanding needs will occur within the next 4 decades, a period also requiring mitigation and adaptation to the resulting substantial changes in land use and climate (Godfray et al., 2010). Understanding, predicting and managing the environmental processes that define the natural capital of Earth's Critical Zone is now one of the most pressing societal challenges of the 21st century (Banwart, 2011).

Changes in land use and climate are now forcing rapid and profound changes in the continental surface that require an unprecedented intensity and scale of scientific observation. Furthermore, this effort must focus overwhelming multidisciplinary expertise at specific locations, i.e. observatories, which tackle the highest priority science questions. This approach is essential to achieve the daunting, but essential, pace and extent of research advance to understand, predict and manage the impacts of environmental change. This evidence will be essential to ensure the long-term access of future generations to services such as clean water and sufficient food, and protection from threats such as floods, famine and drought.

This report outlines the science advances that will be necessary to tackle these challenges and documents the links between basic research on Earth surface processes and the global sustainability agenda. Six priority science questions are identified. Tackling these will 1) establish the necessary understanding of how Earth's Critical Zone has formed, evolved and shaped today's environmental processes and Critical Zone services; 2) develop the empirical evidence and mathematical descriptions to predict how the Critical Zone will change during the next decades and centuries; and 3) provide the science evidence and decision support tools that will help shape policy and management options to meet today's needs and to sustain the natural capital of Earth's Critical Zone for future generations.

Critical Zone Observatories

Critical Zone Observatories (CZOs) provide the overarching research framework to advance new knowledge supporting the sustainable management of Earth's Critical Zone. CZOs may be diverse in specific design, but a common feature is that they each provide a multi-faceted and multi-disciplinary approach to observation of the Earth's surface throughout the extent of the Critical Zone. The approach to observation is motivated by hypothesis testing, process understanding and model development, and makes use of multiple sensor and sampling methods. CZOs generally contain high-density instrument arrays that provide continuous and/or time series measurements of coupled process dynamics, particularly where intense biological activity interfaces with hydrology to drive progressive weathering and erosion of geological media.

Text Box 1. The economic goods and services of Earth's Critical Zone.

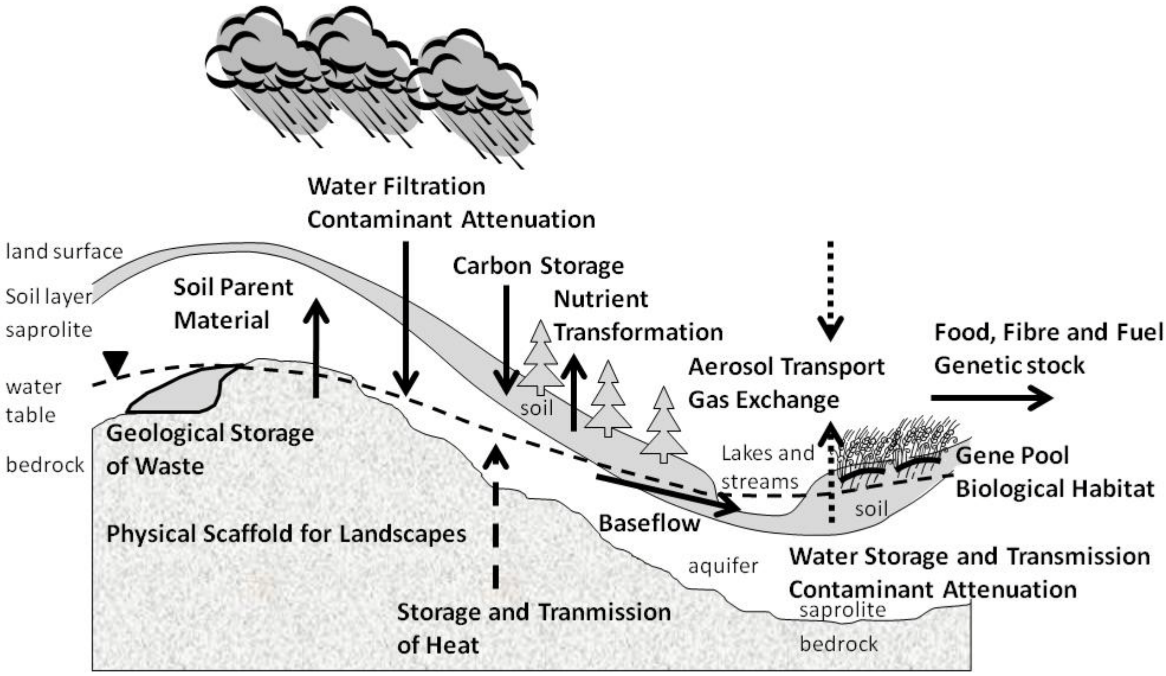

Figure 1. Flows of material and energy in Earth's Critical Zone.

Environmental flows of material, energy and genetic information provide goods and services that benefit humankind. The CZ produces many economically important services (Figure 1). This framework conveys the intrinsic value of sustaining Earth's Critical Zone to supply these flows. Some services hold monetary value in the market, such as biomass crops. Others are outside the market, such as the mineral nutrient supply from rock weathering. "External" services require a means to value them, in monetary terms or other social value including the future value. This allows informed decisions about tradeoffs between alternative management of all CZ services – without compromising their availability to future generations.

The Millennium Ecosystem Assessment (MEA, 2005) describes services that relate primarily to the above ground environment; i.e. ecosystem services. The EU Thematic Strategy for Soil Protection (European Commission, 2006) describes the economic services as soil functions. These include biomass production; storing, filtering and transferring water, carbon, nutrients and contaminants; maintaining habitat and gene pool; sources of raw materials; and as a physical and cultural environment for building and recreation.

The Critical Zone concept provides a powerful interdisciplinary framework for quantifying environmental flows and the goods and services that arise from them. This vertical integration of Earth surface processes spanning the entire CZ, from the top of the tree canopy to the bottom of aquifers, is essential to understanding the full impacts of environmental change. The chain of impact from change in any one part of the Critical Zone can be tracked through the entire system. This includes evaluating different adaptive strategies and assessing the full value, monetary or otherwise, of different management decisions.

A global array of CZOs would represent a network varying across a wide envelope of climatic, lithological, and ecosystem conditions in order to better resolve how this zone forms and functions in order to provide the essential economic services and life support for humanity. Each CZO involves co-located research conducted by interdisciplinary teams comprising geomorphologists, geochemists, hydrologists, ecologists, and other experts. The suite of measurements may include determination of land-atmosphere exchange of water and carbon, event and seasonal changes in soil moisture, pore water chemistry and linkages to biosphere and surface and ground water systems, and associated long-term evolution of the soil, underlying parent material from which it forms, and fractured bedrock permeated by these flows.

A primary goal of these observatories is also to provide the resulting comprehensive data sets to the community of Earth surface scientists for hypothesis testing, integrated model development and as test beds to ground-truth remote sensing technology and geospatial data.

Policy drivers for environmental sustainability, such as the EU Thematic Strategy for Soil Protection, are extending the remit of CZOs, to link with social sciences such as ecological economics and human geography, and the interface with public policy (Banwart, 2011). This creates the opportunity for new interdisciplinary solutions that continue to build on basic science excellence for the study of Earth surface processes, and applying it for predicting, managing and sustaining vital CZ services worldwide. Some examples of Critical Zone Observatory infrastructures and approaches are described in the recent special issue of Vadose Zone Journal on Critical Zone Observatories (Vadose Zone Journal, 2011).

International Critical Mass

Critical Zone research was initiated in 2007 with a $15M (€11M) programme by the USA National Science Foundation to support 3 CZOs, with a doubling of support for a further 3 CZOs in 2009. A 7€M ($9M) programme of research was funded in 2009 by the European Commission (EC), to establish an international network of 12 observatories in Europe, China and USA, with a mandate to work with North American scientists. The French RBV (Network of River Basins) network includes 20 CZO sites worldwide that are already funded (and will remain funded) and is recognized officially by the French Ministry of Research. In Autumn 2011 RBV was awarded 7€M over ~10 years for the CRITEX (Critical Zone Programme of Excellence) equipment and infrastructure programme to support the CZOs. RBV will link with the USA and EC projects. A German CZO led by TUM (Technische Universität München) is working with the EC programme.

This major expansion of CZOs worldwide during the past 5 years is driven both by an agenda to advance new knowledge in Earth surface processes and the need for better scientific evidence for new policy on environmental sustainability. Scientists from approximately 60 observatories located in 25 countries (Figure 2) are now actively engaged in developing a concerted international research effort that explicitly links CZOs and Critical Zone research to the global sustainability agenda. Fundamental challenges in Critical Zone science (Anderson et al., 2004) include the vertical integration of the complex interactions of biological, hydrological, chemical, and physical processes through the full depth of the CZ (Figure 3a).

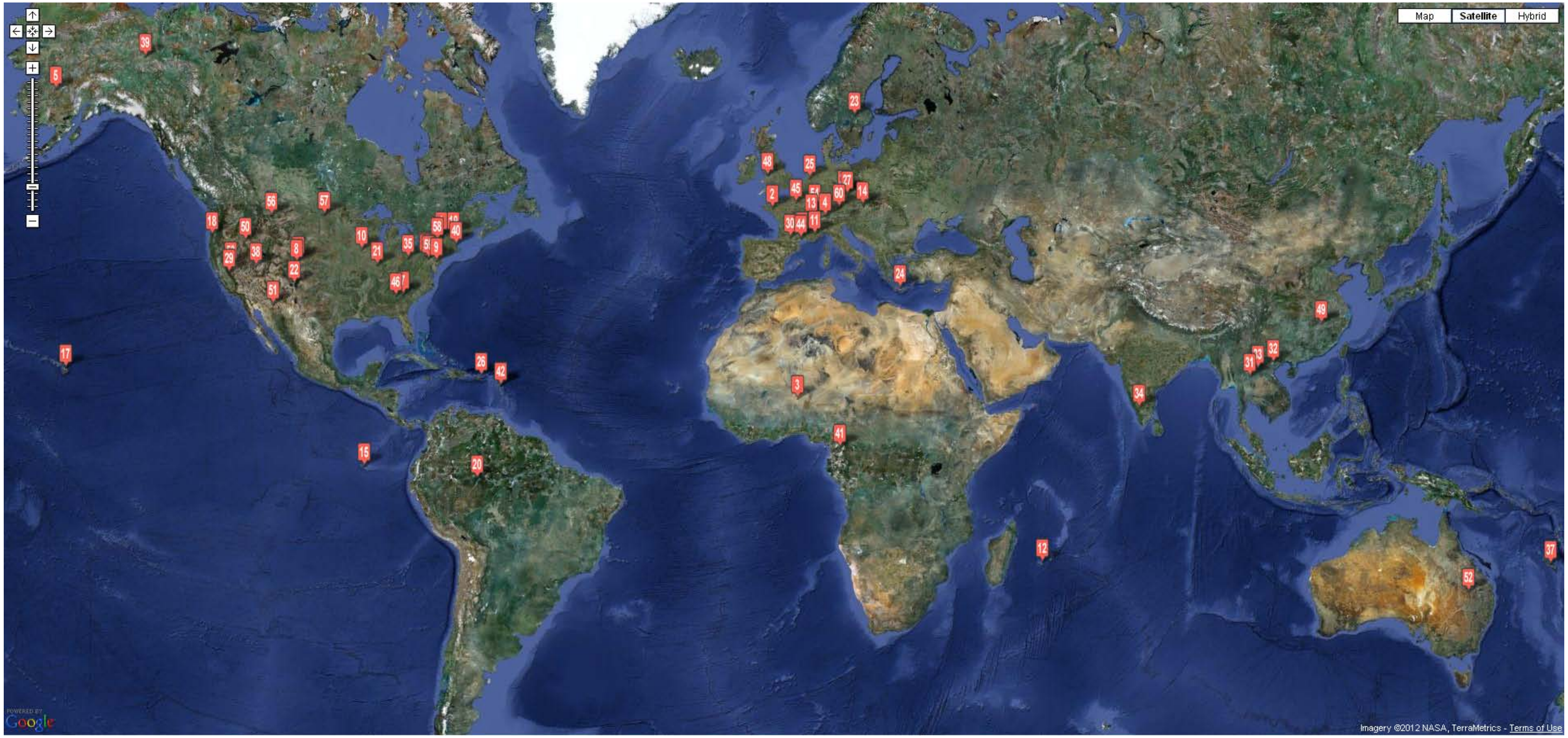

Figure 2. World satellite map with locations of current CZOs presented at the 9th-11th November, 2011 CZO workshop at the University of Delaware, USA. Appendix 3 contains a table of listed sites and locations (see also: http://www.soiltrec.eu/wfieldSites.html). Satellite map provided by Google Earth.

Figure 3a. The vertical architecture of Earth's Critical Zone at the Plynlimon Critical Zone Observatory, Wales. Photo provided by NERC Centre for Ecology and Hydrology, Bangor, Wales.

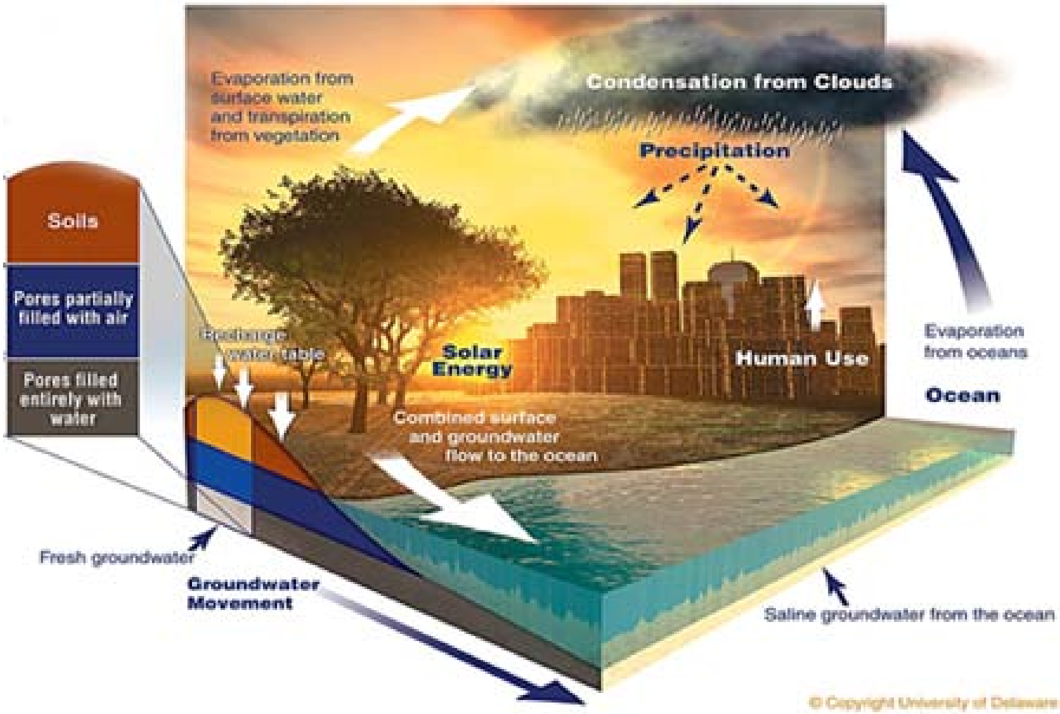

Figure 3b. Landscape diagram showing spatial variability of Earth's Critical Zone. Image copywrite, The University of Delaware, USA.

A further challenge is the need for data and process descriptions across ranges in physical scale from molecular to planetary, and the need to predict the variation in these processes and their intensities from an expanding array of geospatial data. Ultimately, CZ science seeks to quantify and map environmental change and impacts across Earth's landscapes (Figure 3b). A further challenge is translation of knowledge about Critical Zone processes and function, into a quantitative description of economic services arising from these. This must also be incorporated into quantitative decision support tools that help environmental managers and policy makers evaluate the pros and cons of alternative, and sometime conflicting, interventions to mitigate change or adapt to it.

The Critical Zone Impact Chain of Environmental Change

The DPSIR framework (Drivers, Pressure, State, Impact, Response; Figure 4) describes the causal linkages between the societal drivers of environmental change, the resulting changes in Critical Zone processes, and the human response to mitigate or adapt.

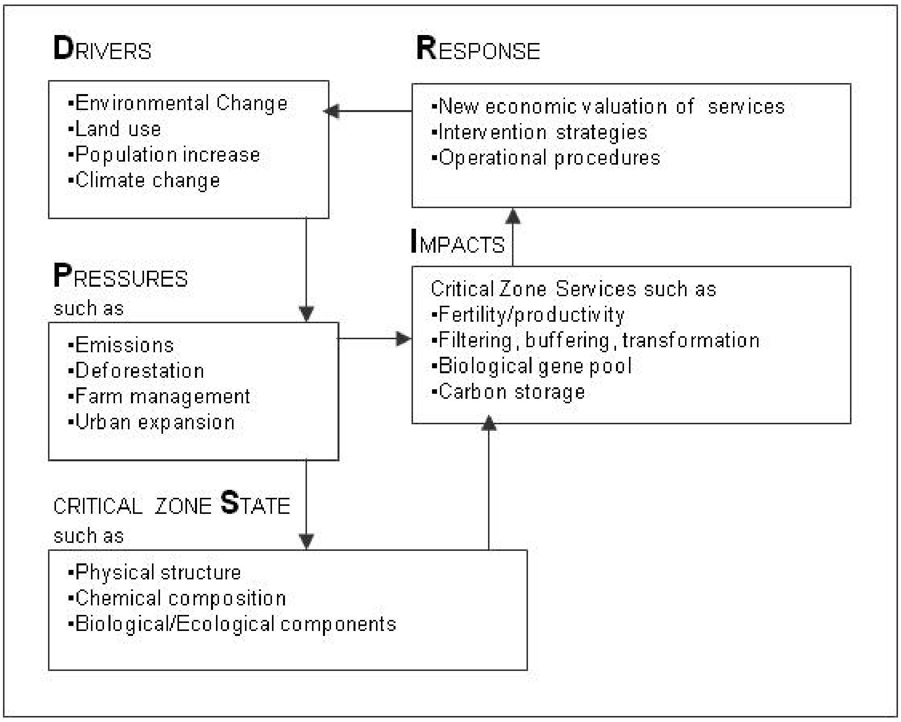

Figure 4. A diagram of the DPSIR framework applied to CZ threats and impacts on CZ Services.

These linkages and feedbacks illustrate how policy and other management interventions rely heavily on interdisciplinary science evidence. The necessary policy responses to environmental change demands that CZ sciences understanding is developed along the chain of impact, first by quantifying the environmental pressures arising or anticipated from the drivers of change; e.g., the environmental forcing. These pressures include increased extreme events from climate change, or the increased demand in food, clean water and fuel driven by population growth. Critical Zone science is required to understand, quantify and predict the resulting change in the environmental state of the CZ, e.g. the conditions that occur. Critical Zone processes respond to these state changes, and result in altered rates of the material and energy flows that yield goods and services. Fully characterizing this chain of causality is crucial to provide the scientific basis for policy and management decisions. This characterization allows greater confidence in choosing where and how to intervene along the impact chain in order to mitigate change or adapt to it.

International Workshop Activities

Critical Zone Observatories provide an exciting and unique opportunity to focus a critical mass of the best multidisciplinary talent worldwide on studying complex and diverse Earth surface processes. This will enable a step change in

1) The capability to predict the geographical variability in current day CZ processes and states from geospatial data and the past record of environmental forcing and impacts, and

2) The ability to predict the future impacts of current and anticipated environmental change.

Eighty-seven representatives (Appendix 1) from 60 CZOs, and leading independent environmental scientists, from around the world met during 9th-11th November 2011 at The University of Delaware, USA. The meeting evaluated the range of international capacity for CZO research. The primary activity was intensive workshop sessions to prioritise the most pressing science questions and the most promising research advances, to be tackled in the coming decade. This document is the initial output from the meeting and provides a road map for establishing global collaborative research, within international networks of CZOs located along planetary-scale gradients of environmental change.

Six Science Questions

Six science questions were circulated ahead of the meeting, debated within the research groups, and revised and adopted according to the consensus views that emerged. The six questions were divided into those addressing long-term processes and impacts driven by environmental forcing over geological time scales; and those addressing short-term environmental change driven by human activity.

Long Term Processes and Impacts

1. How has the geological evolution of the regolith (the portion of the critical zone consisting of loose heterogeneous material covering solid rock) established the ecosystem function and sustainability within earth's critical zone?

2. How do molecular-scale interactions dictate processes in soil and underlying rock, and influence the development of watersheds and aquifers as functional geophysical units?
3. How can theory and data be combined across scales of observation from molecular- to global- in order to interpret past changes in Earth's surface and forecast Critical Zone evolution and its planetary impact?

Short-Term Processes and Impacts

4. What controls the resilience, response and recovery of Earth’s critical zone and its services to perturbations such as climate and land use changes, and how can this be quantified through observations and predicted through mathematical modelling?
5. How can sensing and monitoring technology, e/cyberinfrastructure and modelling methods be integrated to enable the simulation of essential terrestrial variables and forecasting for water supplies, food production, biodiversity and other major benefits for humankind?
6. How can theory, data and mathematical models from reactive transport, biogeochemistry, ecology, economics, law, management science and other disciplines be integrated to simulate, value, and manage Critical Zone goods and services?

Summary of Working Group Outputs

The following 6 text boxes summarise the outputs from the working groups tackling each question.

Science Question 1

How has the geological evolution of the regolith (the portion of the critical zone consisting of loose heterogeneous material covering solid rock) established the ecosystem function and sustainability within earth's critical zone?

Knowledge Gaps/Research Challenges:

- Influence of bedrock on the response of an ecosystem to environmental change.
- Bedrock properties that best predict the structure and function of the CZ from changing external forcing.
- Methods (e.g. geophysical) that will allow enhanced study of the CZ.
- Empirical and/or physically based functional relationships for regolith formation and transformation.
- Mapping fracture orientation/density, parent material chemistry and mineralogy to characterize subsurface structure of regolith.

Hypotheses Developed:

- Long-term CZ evolution is defined by the energy inputs from gravitational (water) and chemical (biological and atmospheric) sources. The response of the CZ to energy inputs is non-linear with threshold changes in state.
- Pathways of water movement and nutrient cycling in the CZ are governed by rates and processes of regolith transformation and also regulate their trajectories.
- Regolith formation rates can be predicted from functional relationships among bedrock porosity, permeability (including fracturing), chemistry, and mineralogy.
- The structure and fabric of the CZ both depend on and regulate biological composition and activity thus influencing rates of regolith formation.

Experimental Design and Method (or Measurements):

The current state of the CZO network does not provide a sufficient number of sites that span different soil residence times on different lithologies. Many CZOs are in orogenic zones in temperate environments where surficial materials have been rejuvenated by glaciation and related processes. To achieve a range of regolith residence times requires CZOs in post-orogenic environments. Key measurements include regolith residence time (aided by new measurement and modelling approaches to defining regolith thickness) and fundamental controls on residence time such as relief and hillslope length. Lithologic reactivity (chemistry, mineralogy, porosity), energy inputs (aspect, insolation, carbon, microbial and vegetation community, etc), weathering solution chemistry and weathering products must be characterized. Methods for regolith study should include coring, geophysical surveys at hillslope scale, and airborne geophysics.

Future CZO Network:

The CZO network must include multiple lithologies (e.g. granite vs. basalt) to define different sensitivities to major perturbing forces – e.g. erosion, acidic leaching. To capture regolith development, chronosequence concepts for hillslopes within climosequence should be included. This provides a problem and an opportunity: the problem is to define the variation in paleoclimate before we have an understanding of the integrated energy input. The opportunity is to define climate perturbation sequences (e.g. different intensities of glacial – interglacial climate change).

Science Question 2

How do molecular-scale interactions dictate processes in soil and underlying rock, and influence the development of watersheds and aquifers as functional geophysical units?

Knowledge Gaps/Research Challenges:

- The effect of brief high intensity events vs. low intensity persistent process rates (frequency, intensity).
- The cause of biogeochemical hotspots/hot moments (spatial heterogeneity).
- The primary criteria for selecting a watershed and the monitoring methods.
- Geophysical monitoring of processes.
- Knowledge of interfaces (plant/surface/soil, soil/rock, weathered rock/fresh rock, water table)

Hypotheses Developed:

- CZ structure and architecture can be predicted from knowledge of initial conditions and forcing (climate, tectonics, lithology) and steady process rates.
- Up scaling from short to long timescales can be accomplished

Experimental Design and Method (or Measurements):

This vision requires comprehensive measurements to characterize geology, soil type, topography, regolith depth, vegetation, land–atmosphere fluxes (water, solar energy etc), soil moisture/potential, groundwater elevation, soil water chemistry, and microbial community (composition and function). At the watershed-scale, measurements must include discharge, groundwater monitoring, subsurface temperature, sediment yields, chemical mass balance, soil water and organic carbon.

Future CZO Network:

The existing and expanding CZO network of sites and scientific expertise provides enhanced opportunities to work across a global CZ DPSIR framework (figure 4). This network will help us to understand the changing role of the CZ in delivering goods and services as global change accelerates, and it could help us to develop a major new scientific community. This new community and its inter-disciplinary approach will be possible by virtue of a common scientific language and networked CZO research platform.

Science Question 3

How can theory and data be combined across scales of observation from molecular- to global- in order to interpret past changes in Earth's surface and forecast Critical Zone evolution and its planetary impact?

Knowledge Gaps/Research Challenges:

- CZ influence on the response of carbon, sediment, energy and water fluxes to climate change.
- Prediction of CZ architecture and how it will transform under perturbation at a previously unstudied site.
- Response of the CZ to the Pleistocene to Holocene (glacial to postglacial) transition, and what parameters best codify the history?
- The role of the deep CZ in climate?
- Development of a 1D CZ model.

Hypotheses Developed:

The response of soil/ecology/water resources to the impulse of future global climate change can be predicted using CZO experience.

Experimental Design and Method (or Measurements):

Detailed measurements of chemistry, mineralogy, saturated hydraulic conductivity, cosmogenic nuclides and other isotopic measurements, carbon/microbial biomass, porosity, moisture content, fracture density/ surface area, subsurface data using geophysical tools, soil description, etc., are necessary.

Future CZO Network:

The CZO network could be used for a “Drill the Ridge” campaign to study sequences or “gradients” of variables (Variables include lithology, climate, channel incision etc.) and help to develop a 1-Dimensional CZ process model.

Science Question 4

What controls the resilience, response and recovery of Earth's critical zone and its services to perturbations such as climate and land use changes, and how can this be quantified through observations and predicted through mathematical modelling?

Knowledge Gaps/Research Challenges:

- There is a lack of information on thresholds; e.g. how far can the CZ system be stressed before a tipping point is reached?.
- What controls system sensitivity? What can change and what must remain unchanged (keystone processes/species, causal linkages) to maintain key CZ processes and services, and what factors control that sensitivity (different in riparian zones, permafrost, grasslands)?
- What engineering strategies can be applied to modify, recover or sustain CZ services, e.g. soil fertility.

Hypotheses Developed:

- What can and cannot be predicted about CZ systems? What are the limits to the predictability of CZ processes and state-dependent responses to perturbation.
- Humans can successfully manipulate CZ processes to maintain soil fertility or water quality sustainably in the face of constrained global change; i.e., within some tolerable range. However, we do not yet understand the recoverable range for all important constituents, processes, and systems.
- Spatial and temporal scale of CZ response to perturbation can be predicted given knowledge of the spatial and temporal scale of disturbance as well as system state (lithology, biota, climate).

Experimental Design and Method (or Measurements):

Integration of ecology is important for fully integrated CZO studies. Measurements may include climate parameters, energy, water, carbon, nutrient fluxes (input and output), biology, food web, hydrology and sediment measurements and geophysical measurements (ground and airborne-based).

Future CZO Network:

The CZO network is an opportunity to systematically characterize disturbance and land use (anthroposequence). Many additional sites are available to study specific gradients (e.g. climosequence).

Science Question 5

How can sensing and monitoring technology, e/cyberinfrastructure and modelling methods be integrated to enable the simulation of essential terrestrial variables and forecasting for water supplies, food production, biodiversity and other major benefits for humankind?

Knowledge Gaps/Research Challenges:

- An international CZO governance structure is needed to facilitate the desired level of integration, including: definition of the requirements for membership in the CZO governance and the benefits of membership; and, formalization of the process for establishing satellite sites.
- A framework is needed for open and integrated CZO data and model sharing.
- A process is needed for determining core sets of instrumentation and observations.

Hypotheses Developed:

- Current technology can be successfully and affordably harnessed to dynamically link national geospatial datasets, numerical models of CZ processes, and specialist research data sets in order to parameterise and apply process simulations at landscape to continental scale.
- CZOs can be used as critical test beds that provide data sets to groundtruth geospatial remote sensing methods and data.
- CZOs can provide essential process understanding in order to reliably downscale change pressures and upscale change impacts between landscape and continental/global scale.

Experimental Design and Method (or Measurements):

Strategies and Requirements

- Provide input to improving the land component of global Earth system models, and provide verification data sets to test the impacts of global change.
- Adopt a strategy for developing and testing models capable of forecasting over increasingly larger scales of CZ processes.
- Conduct campaigns that enable cross-CZO and CZO-network science.
- CZO program should: use models for network design (e.g. identify missing measurements/data); leverage existing networks to advance CZ science; provide access to essential terrestrial data for all CZO sites; develop a community strategy for models and data that scale/leverage existing CZO research; reconstruct environmental histories to deconvolve climate and land use change effects; and, evaluate uncertainty in measurements and models

Science Question 5 - Continued on following page

Science Question 5 - Experimental Design and Method - Continued:

Implementation

- Perform a model intercomparison project from CZO characterization data sets of water and energy, biogeochemistry, plant dynamics, and landscape evolution.
- Provide CZ reconstruction experiments/products such as vegetation and hydroclimatic histories, soil morphology and evolution, and rock weathering.
- Provide predictions for sustainable and secure use of the CZ (soil, water, plants, rock) and CZ services (energy, food and water)
- Complete a CZO data infrastructure including geospatial and temporal data and models, OGC data standards, protocols and tools for uncertainty documentation and evaluation, and access to the following information:
  - land cover (NLCD, LANDSAT, MODIS, high resolution multispectral products, wetlands inventory)
  - Land use and land management
  - Vegetation (biomass, NPP, LAI, structure, etc.)
  - Soil classification mapping (SSURGO, JRC, global)
  - Topography (DEM, lidar)
  - Climate and weather
  - Geology (including geophysical surveys from ground, air, satellite)
  - Streamflow, bathymetry, chemistry, sediment, etc.
  - Groundwater (level, flux, energy, chemistry, etc.)
  - Soil moisture, temperature, chemistry
  - Snow (depth, SWE, chemistry, structure)
  - Soil biotic indices (ecozone, soil microbial classification, etc.)

Future CZO Network:

The CZO network should advance robust predictive understanding of the structure, function and evolution of the CZ. The rationale for site inclusion and gradient-based site design should be oriented towards CZ-specific predictions that will ultimately scale up to the terrestrial Earth. CZOs should be testbeds for theory, models, methods, and experiments as an ongoing continuous process, and should facilitate international network-level model-driven research campaigns.

Science Question 6

How can theory, data and mathematical models from reactive transport, biogeochemistry, ecology, economics, law, management science and other disciplines be integrated to simulate, value, and manage Critical Zone goods and services?

Knowledge Gaps/Research Challenges:

- Lack of integration of disciplines, and scales (processes or disciplines dependent).
- Long-term effects of human adaptation of the landscape.
- Incorporation of the slow response of human feedback.
- Study of systems in transition, near a tipping point or threshold, provide more knowledge and insight than those that are not.
- Prediction of services cannot be accomplished using the typical variables that are currently measured or predicted (e.g., food/biomass prediction is possible; but C sequestration is not).
- The diagnostic metrics (indices) that can improve space-time representation and be used to frame hypotheses across disciplines to classify the structure of the CZ system.
- The master variables that characterize CZ system structure and response, e.g., biology and people respond quickly to CLORPT (climate, organisms, relief, parent material, time) and have a long-term signal throughout CZ.
- The response of the CZ to the Pleistocene-to-Holocene transition.

Hypotheses Developed:

- Existing theoretical frameworks and observation methods, can be integrated across natural and social sciences and thus provide quantitative, interdisciplinary methods to analyse and predict the impact of human intervention on CZ processes and services.

Experimental Design and Method (or Measurements):

- CZOs tackling these hypotheses must incorporate a far greater range of observations and data than those used in current CZ research programmes.
- CZO network needs shared indices/master variables/diagnostic metrics that include a greater disciplinary breadth, such as: CLORPT, Horton index = ET/(P-quick flow) is constant from year to year for a catchment and strongly related to productivity, and social indices on change adaptation; i.e. diet, wealth, education.

Future CZO Network:

The CZO network will enable scientists to study transitions and predict/earthcast environmental thresholds and tipping points resulting from, e.g. climate change, land use change etc. The network will also: help to understand the robustness of CZ services and how CZ services (food, biodiversity, C sequestration and water filtration) are affected by change; be used to study big global challenges of land use and will help integrate all CZ services. The network could be used for studying various chronosequences of: restoration, arable land, geocomposition, climate, human intensity, etc. Selection criteria for the CZO sites should include a chronosequence of restoration and disturbance in relation to soil ecosystem services. This will help to recreate a life history of land use, constructing and simulating the narrative of a site, identifying critical transitions, and identifying areas and methods for restoration.

Funding Opportunities

Both national and international funding possibilities (including private foundation funding) should be explored for the future CZ research. The new CZOs have to be identified and established according to the necessary experimental design to address the six, key scientific questions; this needs both national and international support. Funding is also needed for an international exchange program for scientists and students.

National funding agencies have to step up their efforts (e.g. joint international funding or with private foundation funding) to support integrated international projects in the future. There is a need to explore the opportunities from several private funding sources that are supporting international research projects. Participating countries will also have to submit proposals in parallel for instrumentation and data collection from the existing or new CZOs.

International Earth Observation Infrastructure

CZOs provide an essential contribution of Earth Observation geospatial science. They provide the detailed data sets to groundtruth satellite and other remote observation methods. The mathematical models of CZ processes provide the information link between national geospatial data, model parameterisation, and upscaling of process rates and impacts to continental scale. An essential next step is to integrate CZOs with the Global Earth Observation System of Systems (GEOSS) initiative of the GEO intergovernmental framework on Global Earth Observation. CZOs provide particular strengths to help deliver GEOSS priority areas of environmental factors for human wellbeing, predicting climate change, managing water resources, and managing terrestrial ecosystems.

Next Steps

The current scale of international integration of CZ research is identified by the workshop participants as a major strength. This provides a valuable platform to build upon, in order to create a programme of research with global reach geographically and in impact. Expanding the international scope, the participation and the degree of integration, is agreed as an essential step to deliver the necessary science advances and the evidence for policy decisions. The 6 priority science questions can be addressed successfully if they are tackled by following an integrated, interdisciplinary and international approach. The workshop participants also agreed that CZ research must include more disciplines, particularly to strengthen biological and social sciences.

Though hypotheses developed by the various workshop groups are different depending on the research questions discussed, nevertheless there is a general consensus on the approach. This emphasises development of a broad interdisciplinary research methodology that is applied to groups of sites selected along environmental gradients at large geographical, up to planetary, scale (see Text Box 2).

Text Box 2. Environmental Gradients for experimental design using networks of CZOs at planetary scale.

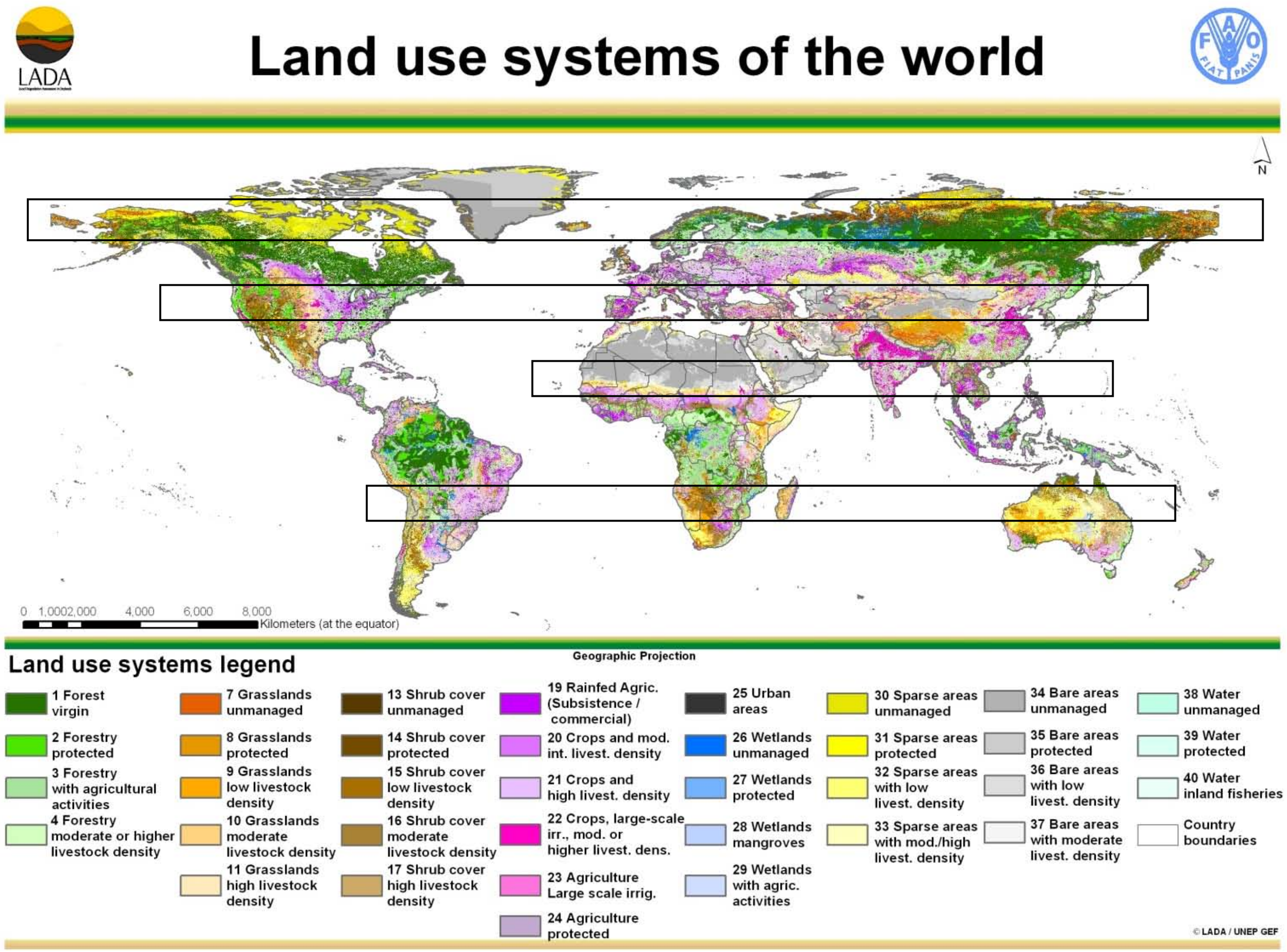

Figure 5a. Global map of land use systems. East-West trending zones of variable land use are marked as boxed areas within broadly similar climate zones. Experimental design includes networks of CZOs located along gradients of land use intensity in these or other zones. CZO data, models and decision tools can assess the sensitivity of Critical Zone processes and services to land use. This would provide evidence to assess the impacts of land use change and to design and test intervention strategies to mitigate or adapt to adverse impacts. For example afforestation programmes in The Sahel or North-West China could be used to assess the sensitivity of dryland CZ processes to changes in vegetation cover. Map available from UN Food and Agriculture Organisation, Land Degradation Assessment in Drylands.

Text Box 2 - Continued. Environmental Gradients for experimental design using networks of CZOs at planetary scale.

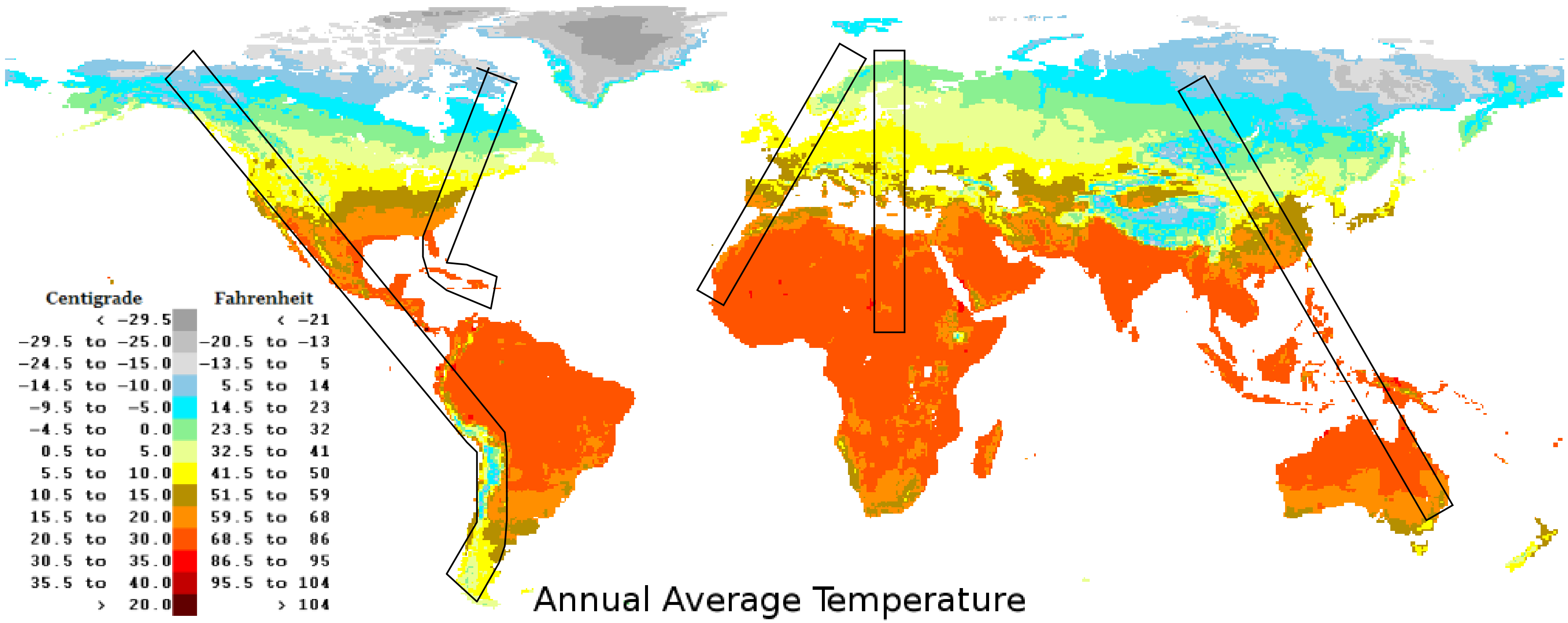

Figure 5b. Global map of average annual temperature with North-South trending climate gradient zones noted as boxed areas. Experimental design can include networks of existing and new CZOs located along the gradients in these or other zones. CZO data, models and decision tools will shed light on the sensitivity of Critical Zone processes and services to climate variation, and provide evidence to design intervention to mitigate or adapt to adverse climate change impacts. For example, current N-S temperature trends along CZO networks can shed light on the sensitivity of CZ processes and services to future climate change. These networks provide testbeds for intervention strategies to mitigate or adapt to the impacts of change on CZ services. Map available from World Climate. http://www.climate-charts.com/index.html

Additional data collection campaigns (e.g. ridge-top and geophysical measurements) are to be included to answer some of the key questions on evolution of CZ and Earthcasting. Inclusion of various gradients (e.g. chronosequence) or anthropogenic influence (e.g. anthroposequence) must be integrated further in CZ research in order to learn how to tackle CZ complexity, pick apart process interactions and identify CZ state thresholds to maintain key functions and services. Increasingly general, and thus more reliably transferable between locations, descriptions of processes are being developed by bridging observations scales from molecular to catchment and larger. Interpreting the historical record, characterising spatial heterogeneity in environmental conditions and intensity of services, coupling process descriptions across spatial and temporal scales, building the computational and data infrastructure to integrate information, effective synthesis of science evidence to support policy and management; these are the challenges ahead in CZ research.

Specific measurements will depend on the scientific questions and the sites required in the experimental designs; however, data on baseline measurements are needed to establish current conditions as a benchmark, and need to be shared across the network. The future CZO networks require governance; to follow a set of guidelines on CZO capability, institutional support, data collection, and the dissemination and sharing of date and models.

The groups agreed that an international coordination of funding agencies is needed for CZ research. Various national science funding agencies, regional (e.g.EU) and private funding sources (e.g. Bill Gate's foundation) have to be explored. International exchange programs and visits, and public and educational outreach, are all features of existing CZO projects and these need to be strengthened.

In order to advance the international integration, 5 near-term challenges are identified and will be tackled in existing CZO projects across sites.

1. Creation of a web-based global directory of current and candidate CZO sites. This will take place by expanding the information and capability of the SiteSeeker web pages of the Critical Zone Exploration Network (www.czen.org) web site. As an immediate step, site data compiled through this reporting will be incorporated into SiteSeeker.
2. Wide international dissemination is required to build from these workshop outputs and inform researchers and funders in order to advance an international CZ science agenda. This is to advance CZ knowledge and sustainability by recruiting new disciplinary expertise, broadening the geographical footprint of CZO networks along global gradients of environmental change, and extend the global research impact of CZOs.
3. Vertical integration of CZ processes from above ground ecology to below ground geology, in order to identify the impact linkages such as for the DPSIR framework – linking CZ processes and services. This is being led by the EU teams involved in the SoilTrEC project.

4. Compilation of specialist geospatial data such as soil characterisation data in open source web resources that can be integrated with geospatial data products from national agencies. This is being led by US teams from the national CZO programme and the EarthKin open-source data project.
5. Development of a proposal for supplementary funding to build a prototype web service that provides dynamic linkages between national data products, numerical models, and specialist research geospatial data sets. This will be done explicitly to advance international data and modelling integration between projects funded by the NSF and EC CZO programmes and the UK Environmental Virtual Observatory pilot. The aim is to demonstrate the utility of the service to support international integration and expansion of CZO research, and to further develop the model of international collaboration that is currently being used. The supplementary funding will include support as a pilot CZO capability for implementation in the GEOSS initiative.

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Appendix 1 : EU/USA Joint CZO Workshop – Participants List

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Appendix 2: Posters Presented at Joint EU/USA CZO Workshop

	Poster Title	Authors	Institution
1	"lowlands": An Urbanized delta CZO in search of increased sustainability	van Gaans, P.; Sommer,W.; Erkens, G.	Deltares
2	The French Resource for the Exploration of the Critical Zone : the RBV global network	Gaillardet, J.	IPG Paris
3	A proposed observatory for karst critical zone science	Graham, W.; Martin, J.; Cohen, M.	University of Florida
4	Assessing Water Resources by Ground Water Dating in Streams	Solomon, D. K. ; Hollingshaus, B. and Stolp, B.	University of Utah
5	Boulder Creek Observatory, Studying the zone where rock meets life	Anderson, S.; Anderson, R.; Barnard, H.; Blum, A.; Caine, N.; Dethier, D.; Fierer, Hinckley, E.; Leopold, M.; Mcknight, D.; Molotch, N.; Murphy, S.; Ouimet, W.; Pruett, C.; Rock, N.; Sheehan, A.; Tucker,G.; Voelkel, J.; Williams, M.	University of Colorado
6	Cerro Crocker - Pelican Bay Watershed, Santa Cruz Island, Galapagos	D'Ozouville, N. and Violette, S.	Universite Paris
7	Christina river basin critical zone observatory	Sparks, D., Aufdenkampe, A.; Kaplan, L.; Pizzuto, J.; and K. Yoo	University of Delaware
8	Determinations of Sedimentary Fluxes and Their Comparison with Chemical Weathering Fluxes at the Outlet of the Granitic Strengbach Catchment (Vosges massif, Eastern France)	Viville, D. , Chabaux, F.; Stille, P., Pierret, M. C.; Gangloff, S.; Benarioumlil, S.	Centre National de la Recherché Scientfique
9	Development of a Global Geochemical Database for CZEN Applications	Niu, X.; Williams, J.; Jin, L. and Brantley, S.	Penn State University
10	Dynamics of tropical ecosystems in context of global changes (climatic variations/human activities)	Jean, Jacques Braun	IRD - Institut de Researche pour le development
11	Ecosystem Functions in an Urbanising Environment - SEQ peri-urban supersite	Rowlings, D.; Grace, P.; Carlin, G.; Stevens, A.	Queensland University of Technology
12	Importance of satellite sites near Critical Zone Observatories, The GEOMON network of small forested catchments in the Czech Republic, Central Europe	Novak, M.; Krám, P., Fottova, D.	Czech Geological Survey
13	Jemez River Basin and Santa Catalina Mountains CZO	Chorover, J.; Troch, P; Rasmussen, C.; Brooks, P; Pelletier, J.	University of Arizona
14	Long Term Chemical variations in stream waters draining a granitic catchment (1986-2010). Link between hydrology and weathering (strengbach catchment, France)	Pierret, M.; Viville, D.; Chabaux, F.; Stille, P.; Gangloff, S.; Annrobst	Centre National de la Recherché Scientfique
15	LYSINA Critical Zone Observatory - Czech Republic, Central Europe	Krám, P., Hruska, J., Oulehle, F., Lamacova-Bencokova, A., Novak, M., Farkas, J., Cudlin, P., Stuchlik, E.	Czech Geological Survey
16	Modelling anticipated climate change impact on biogeochemical cycles of an acidified headwater catchment	Bencokova, A.; Hruska, J.; and P. Krám	Czech Geological Survey
17	Monitoring of the Kabini watershed	Jean, Jacques Braun	IRD - Institut de Researche pour le development

18	Monitoring riverine sediment fluxes during extreme climatic events: new tools and methods	Jeunesse, E; Delacourt, C; Allemand, P; Limare, A; Dessert, C; Ammann, J; Grandjean, P and Crisp, O	LDFG, IPGP, Paris,
19	Morphological and Physical Characterization of Soil Profiles from the SoilTrEC Project CZOs	Rousseva, S.; Kercheva, M.; Shishkov, T.; Ilieva, R.; Nenov, M; Dimitrov, E.	ISSNP
20	Research areas & key scientific questions addressed at the Koiliaris river basin	Nikolaidis, N.	Technical University of Crete
21	Rivendell: Linking the critical zone to the biosphere, atmosphere and ocean	Fung, I; Cohen,R; Bishop, J; Dawson, T; Power, M, Kaufman, K; Dietrich, W	Berkeley
22	Science and data products at the national ecological observatory network (NEON)	Powell, H; Kampe, T.; Loescher, H.; Berukoff, S.; Schimel, D.	National Ecological Observatory Network
23	Shale to Soil, Geochemistry and Clay mineral transformations	April, R.H; Lemon, S; keller, D	Colgate University
24	Soil transformation in the DANUBE basin CZO Fuchsenbigl-Marchfeld/Austria	Lair, G. and Blum, W.	BOKU
25	Study of the Soil from a Chronosequence and Hydrology of Damma Glacier: CZO Switzerland	Bernasconi, S.	Swiss Federal Institute of Technology
26	Susquehanna/Shale Hills Critical Zone Observatory	Duffy, C; Brantley, S; Davis, K; Eissen Stat, D; Kay, J; Kirby, E; Lin, H; Miller, D; Singha, K; Slingerland, R; White, T	Penn State University
27	The Case for a Prairie Porthole Region CZO	Goldhaber, M; Mills, C; Stricker, C; Morrison, J.	United States Geological Survey
28	The Influence of Age and Climate on Long-term Soil Carbon Stabilization: Implications for Northern Latitudes	Harden, J.; Lawrence, C.; Schulz, M.	United States Geological Survey
29	The Isotopic Composition of Organic Carbon in Adirondack Spodosols	April, R.H , Coplin, A.L	Colgate University
30	The Next Generation Ecosystem Experiments- Arctic	Wullschleger, S.; Hinzman, L.; Graham, D.; Hubbard, S.; Liang, L.; Norby, R.; Riley, B.; Rogers, A.; Rowland, J.; Thornton, P.; Torn,M.; Wilson, C.	Environmental Sciences Division, Oak Ridge National Laboratory
31	The North Wyke Farm Platform	Murray, P.; Orr, R.; Hatch, D.; Griffith, B.; and Hawkins, J.	Rothams`ted Research Institute
32	The Reynolds Creek Experimental Watershed: An Environmental Observatory for the 21st century	Link, T.; Marks, D.; Seyfried, M.; Flerchinger, G.; Winstral, A.	University of Idaho
33	The Southern sierra critical zone observatory	Glaser, S.; Bales, R.; Riebe, C.; Goulden, M.; Conklin, M.; Hopmans, J.; Tague, C.	University of California, Merced
34	The Tenderfoot Creek Experimental Forest: Linking watershed Form to Ecohydrologiocal and Biogeochemical Function	McGlynn, B.; Keane, B.; Jennsco, K.; Riveros-Iregui, D.; Marshall, L.; Stoy, P., Epstein, H.	Montana State University
35	TUM - critical zone observatory - a newly launched research initiative	Voelkel, J.	TUM/TERENO
36	University of Arizona Biosphere 2 Landscape Evolution Observatory	University of Arizona	University of Arizona
37	Using soil spectroscopy to quantify variations in erosion and landscape forcing	Sweeny, K.; Roering, J.; Almond, P.; Recklin, T.	University of Oregon

38	Using time-lapse digital photography to monitor changes in the critical zone	Papuga, S.; Nelson, K.; and Mitra, B.	University of Arizona
39	Watershed Characterization & hydrological functioning (Mule Hole, Forested)	Jean, Jacques Braun	IRD - Institut de Researche pour le development
40	Weathering of the biogeochemical cycles (Mule Hole & gradient)	Jean, Jacques Braun	IRD - Institut de Researche pour le development
41	Luquillo Critical Zone Observatory	Scatena, F.N; Buss, H; Brantley, S.L; White, A.F	University of Pennsylvania
42	RBV: a French critical zone network	Gaillardet, J.	IPG Paris
43	Ecosystem functions in an urbanising environment – SEQ peri-urban supersite	Rowlings, D; Grace. P	Queensland University of Technology

Appendix 3: International CZO Sites
Locator map available online at: http://www.soiltrec.eu/wfieldSites.html

	CZO	Location	Country
1	Adirondack Mountains	South-western Adirondacks	USA
2	AGRHYS	Brittany	France
3	AMMA-CATCH	S-N ecoclimatic gradient in West Africa	West Africa
4	Damma Glacier	Canton Uri, Switzerland	Switzerland
5	Bonanza Creek LTER	Alaska	USA
6	Boulder Creek Critical Zone Observatory	Boulder Creek, Colorado Front Range, Rocky Mountains	USA
7	Calhoun LTSE	Southern Carolina	USA
8	North Central Great Plains	North Dakota	USA
9	Christina River Basin CZO	South-eastern Pennsylvania and Northern Delaware	USA
10	Clear Creek	Iowa	USA
11	DRAIX-BLEONE	6,3° E - 44,1° N, French South Alps	France
12	Rivière des Pluies Erorun	Réunion Island, Indian Ocean	France
13	French Karst observatory	Languedoc, Jura, Provence, Pyrénées, Paris Basin, aquitanien Basin	France
14	Fuchsenbigl	East Austria	Austria
15	Galapagos CZO	Santa Cruz Island, Galapagos Archipelago, Ecuador	Ecuador
16	Guadeloupe	Guadeloupe, French West Indies	France
17	Hawaii	Hawaii	Hawaii
18	Hoffman Creek site	Oregon	USA
19	Hubbard Brook Experimental Forest	New Hampshire	USA
20	HYBAM: Hydrological and geochemical observatory of the Amazon Basin	Amazon drainage basin	Brazil, Peru, Ecuador, Bolivia and France
21	Illinois River Basin	Illinois	USA
22	Jemez River Basin CZO	New Mexico	USA
23	Kindla	Kindla, Bergslagen	Sweden
24	Koiliaris River Basin	East Chania, Crete	Greece
25	Lowlands CZO	Netherlands	Netherlands
26	Luquillo	Luquillo, Puerto Rico	Puerto Rico
27	Lysina	Slavkov Forest	Czech Republic
28	Marcellus shale	Pennsylvania	USA
29	Merced River Chronosequence	California	USA

30	MONTOUSSE	Gascogne	France
31	MSEC (management of soil erosion consortium)	SE Asia (3 sites)	Thailand
32	MSEC Dong Cao long term monitoring catchments	20°57'40"N - 105°29'10"E	Vietnam
33	MSEC Houay Panoi long term monitoring catchments	19°51'10"N - 102°10'45"E	Laos
34	Mule Hole (Bandipur National Park)	Southern India (Mule Hole : 11° 72' N 76° 42 E)	India
35	Muskingum Watershed	Ohio	USA
36	Na Zelenem	Western Bohemia	Czech Republic
37	NC2	New Caledonia	France
38	NevCAN, Sheep Range and Snake Range Transects (NevCAN)	Southern and East Central Nevada	USA
39	North Ogilvie Mountains	Yukon Territory	Canada
40	North-eastern Soil Monitoring Cooperative	North-eastern Soil Monitoring Cooperative	USA
41	Nsimi	Cameroon (Nsimi: 3° 10' N 11° 50' E)	Cameroon
42	OBSERA	Guadeloupe (Lesser Antilles)	France
43	OHM-CV	Cevennes-Vivarais (4 sites)	France
44	OMERE	Brie, Paris Basin	France
45	ORACLE	Languedoc and Cap Bon (two sites)	France and Tunisia
46	Panola Mountain	Atlanta	USA
47	Pluhuv Bor	Slavkov Forest	Czech Republic
48	Plynlimon	Mid Wales	UK
49	Red Soil Site	Yingtan, Jiangxi Province	China
50	Reynolds Creek Watershed	Southwest Idaho	USA
51	Santa Catalina Mountains CZO	Saguaro National Park	North America
52	SEQ peri-urban supersite	South East Queensland	Australia
53	Southern Sierra Critical Zone Observatory	Tucson	USA
54	Strengbach	Vosges Mountains	France
55	Susquehanna Shale Hills Critical Zone Observatory	central Pennsylvania	USA
56	Tenderfoot Creek Experimental Forest	Continental Divide in Montana, southwest Alberta, and Wyoming	USA
57	The Prairie Pothole Region CZO	South Central North Dakota	USA
58	The Rogers Glen (Shale Hills CZO) satellite site	Chadwicks, NY	USA
59	Trindle Road Appalachian Trail Diabase	Pennsylvania	USA
60	TUM Critical Zone Observatory	Bavaria	Germany

END OF CZO WORKSHOP REPORT