Sustaining Earth's Critical Zone

Basic Science and Interdisciplinary Solutions for Global Challenges

Banwart, S.A., Chorover, J., Gaillardet, J., Sparks, D. , White, T., Anderson, S., Aufdenkampe, A., Bernasconi, S., Brantley, S.L, Chadwick, O., Dietrich, W.E., Duffy, C., Goldhaber, M., Lehnert, K., Nikolaidis, N.P, and Ragnarsdottir, K.V. (2013).

CONTENTS

ISBN: 978-0-9576890-0-8

EXECUTIVE SUMMARY

Earth's Critical Zone (CZ), the thin outer veneer of our planet from the top 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 and biodiversity decline, is now one of the most pressing societal challenges of the 21st century. The international CZ science community addressed these challenges at an international workshop, convened November 9th-11th, 2011 at the University of Delaware, USA. This report outlines specific CZ 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, atmospheric composition 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 briefly as follows and detailed in full on page 20 of this volume.

Long-Term Processes and Impacts

1. How has geological evolution and paleobiology established CZ ecosystem functions?
2. How do molecular-scale interactions between CZ processes influence the development of watersheds and aquifers as integrated ecological-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?

Short-Term Processes and Impacts

4. What controls the resilience, response and recovery of the CZ and its integrated geophysical-geochemical-ecological functions to perturbations such as climate and land use changes?
5. How can sensing technology, e-infrastructure and modelling be integrated for simulation and forecasting of essential terrestrial variables?
6. How can theory, data and mathematical models from the natural- and social- sciences, engineering, and technology, be integrated to simulate, value, and manage Critical Zone goods and services?

Critical Zone Observatories (CZOs) are research field sites that provide a major international capability to advance the new knowledge that is required for sustainable management of the CZ. Some common features of current CZOs are a wide range of multidisciplinary expertise that is concentrated in order to deliver transformative science advances; a focus on process studies that are hypothesis driven; and a combination of empirical observation at multiple scales with mathematical modelling and simulation. The USA CZOs are developing advances in sensor technology and real-time data acquisition, integrated with data management, across a range of temporal scales. European CZOs are driving forward integration of science advances with social sciences and policy, and development of decision support tools for policy and management intervention.

The role of CZOs is growing in international impact; they are providing scientific focal points to define the major research questions and drawing together the critical mass of disciplines and talent to rapidly deliver solutions to major societal challenges. This development offers enormous potential for research within international networks of CZOs located along global gradients of environmental change; e.g. in land use and climate. Realising this potential requires a step change in the integration of CZO activities and the related science agendas worldwide. The ambition is within 10 years to transform multidisciplinary knowledge and to discover interdisciplinary solutions that will sustain Earth's Critical Zone. Actions over the coming 3 years to develop this potential include increased international cooperation between funding agencies and stronger international governance, an enhanced directory of current and proposed CZOs and associated field sites, wide international dissemination to a greater array of CZ experts, broad scientific access and contribution to CZO sites and data, recruitment of additional disciplinary expertise and CZOs for research along global environmental gradients, and a prototype web service to dynamically link national geospatial data, numerical models and research data.

Workshop Organising Committee

Steven Banwart

Jon Chorover

Donald Sparks

Tim White

Working Group Leaders

Suzanne Anderson

Anthony Aufdenkampe

Stefano Bernasconi

Susan Brantley

Oliver Chadwick

William Dietrich

Chris Duffy

Jerome Gaillardet

Martin Goldhaber

Kirsten Lehnert

Nikolaos Nikolaidis

Vala Ragnarsdottir

EARTH'S CRITICAL ZONE AND GLOBAL SUSTAINABILITY

Earth's Critical Zone (CZ), a phrase suggested by the U.S. 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 Critical Zone is a complex natural reactor, where inputs of solar energy and atmospheric deposition and gases interact with the biota and rock mass of the continents to maintain soil, nourish ecosystems and yield clean water (Anderson et al., 2004; Brantley et al., 2006). The wide range of physical, chemical and biological mechanisms interact at different timescales ranging from seconds to 1000s of millennia, and at spatial scales of single molecules to the entire Earth (Brantley et al., 2007). This diversity of interactions presents an enormous scientific challenge to understanding the linkages and chain of impacts that occur between the many, dynamic components of the Critical Zone. This challenge requires a new, synergistic approach to science where theory and observation are integrated across a wide range of disciplines. Research collaboration comprising geomorphologists, geochemists, hydrologists, soil scientists, ecologists, and many other experts is advancing Critical Zone understanding and its application to sustaining the needs of humanity (Richter and Mobley, 2009; Lin, 2010).

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 well over 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; Reid et al., 2010) and biodiversity decline. 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 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 respond 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.

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

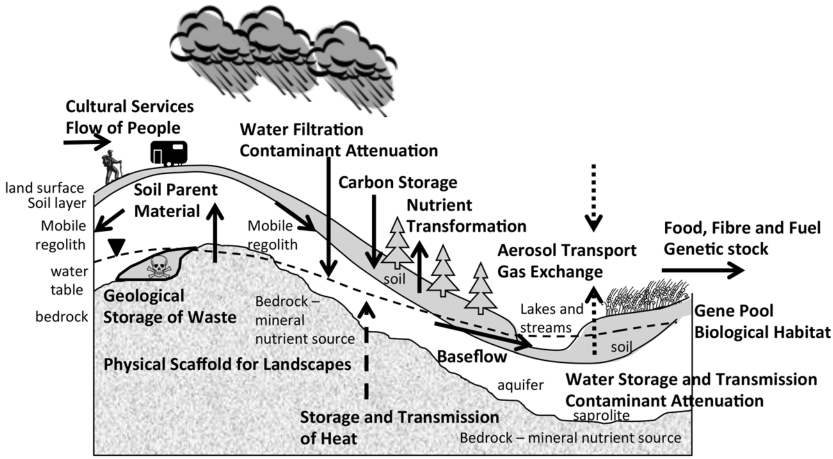


Figure 1. Flows of material and energy in Earth's Critical Zone
Adapted with permission from Banwart et al. (2012).

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 bedrock weathering. "External" services require a means to value them, in monetary terms or other social value including their 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 value, monetary or otherwise, that arise from different management decisions.

CRITICAL ZONE OBSERVATORIES

Critical Zone Observatories (CZOs) provide the overarching research capability 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 mathematical 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.

Each CZO involves co-located research conducted by interdisciplinary teams. The suite of measurements includes determination of land-atmosphere exchange of water and carbon, event and seasonal changes in soil moisture, pore water chemistry and linkages to the 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 testbeds to ground-truth remote sensing technology and geospatial data. This integrated approach also enables CZOs to act as prototypes for long-term observation anchored at specific locations, and to test the potential application of real-time forecasting for CZ processes and services in response to environmental change and human intervention. A number of examples of Critical Zone Observatory infrastructures and approaches are described in a 2011 journal issue on Critical Zone Observatories (Vadose Zone Journal, Vol. 10, 2011).

The ambition and clear potential of this scientific approach is a global array of coordinated CZOs that represents a network varying across a wide envelope of climatic, lithologic, and ecosystem conditions in order to better resolve how this zone forms and functions and provides the essential economic services and life support for humanity.

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 €7M ($9M) programme of research was funded in 2009 by the European Commission (EC), to establish an international network of observatories in Europe, China and USA, with a mandate to work with North American scientists. The French RBV (Network of River Basins) network, 20 CZO sites worldwide founded by governmental agencies, was awarded €7M over ~10 years for the CRITEX (Critical Zone Programme of Excellence) equipment and infrastructure programme to support the CZOs. RBV has links with the USA and EC projects. A German CZO led by TUM (Technische Universität München) is working with the EC programme.

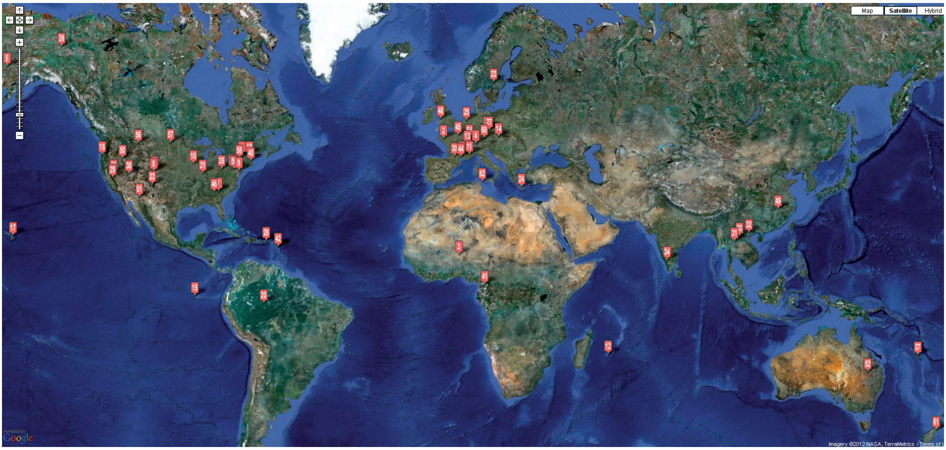


Figure 2. World satellite map with locations of current CZOs and related study sites presented at the 9th-11th November, 2011 CZO workshop at the University of Delaware, USA.

Appendix 2 contains a table of listed sites, location, and contact information. Satellite map provided by Google Earth.

The USA CZO programme pursues basic geosciences research of CZ processes and is developing novel observation methods using in situ and real-time sensing at a range of temporal scales and spatial density (see e.g., Vadose Zone Journal Special Issue on CZOs; Bales et al. (2011); Jin et al. (2011)). The EC CZO project draws largely on existing infrastructure and data and focuses on integration and interpretation of data through mathematical modelling. This is to provide science evidence for implementation of the EU Thematic Strategy for Soil Protection, including a remit to link with social sciences such as ecological economics and human geography, and the interface with public policy (Banwart et al., 2011). The French RBV Network of River Basins includes sites worldwide for research and the monitoring of land-water interactions. This data supports basic geosciences research and provides quantification of environmental processes for resource management.

These three CZO programmes represent a common approach of observatory science applied to the study Earth's Critical Zone. The associated networks of CZOs emphasise different aspects of CZ science and represent 3 important case studies of international CZO networks. These are outlined in Text Boxes 2-4 on the following pages, providing an overview of the scope of CZO research that is currently underway, and demonstrating the current level of collaboration between these research programmes. 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.

This major international expansion of CZOs 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 study sites 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 include the vertical integration of the complex interactions of biological, hydrological, chemical, and physical processes through the full depth of the CZ (Figure 1).

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.

Text Box 2. Case Study – NSF Critical Zone Programme

Web Site: www.criticalzone.org

Funder: USA National Science Foundation, Geosciences Directorate, Earth Sciences Division

Research Focus: interdisciplinary approach to Earth surface processes including geology, hydrology, soil science, geochemistry, geomorphology, biology, ecology and more.

Network governance: overseen by Critical Zone Observatory Principal Investigators and a National Coordinator with an advisory steering committee

Research Objectives

Critical Zone Observatories are environmental laboratories established to study the chemical, physical and biological processes that shape the Earth's surface. CZO research seeks to understand these couplings through monitoring and modeling from the physical and temporal scales of molecular processes to the dynamics of entire watersheds. These studies provide fundamental understanding about how the Critical Zone evolves over geological time scales, including predictions of its response to future changes in climate and land use.

Expected Knowledge Advances

Over the next decade, the CZO program will produce a fundamental understanding and four-dimensional data sets that will stimulate, inspire, and test the resulting predictive models.

The main goals of the program are to develop:

1. A unifying theoretical framework of Critical Zone evolution. The CZOs are working toward a holistic conceptual model of Critical Zone evolution that integrates new knowledge of coupled hydrological, geochemical, geomorphic, and biological processes including both positive and negative feedbacks and their distribution in time and space.
2. Coupled systems models to explore how Critical Zone services respond to anthropogenic, climatic, and tectonic forcing - building systems models that quantitatively combine multiple processes, often spanning a whole watershed. These models typically track fluxes and storage of energy, water, carbon, sediments, and/or other materials.
3. An integrated data/measurement framework sufficient for documenting a range of geologic and climatic settings, informing our theoretical framework, constraining models, and testing model-generated hypotheses across a CZO Network by assembling the needed infrastructure for an integrated data/measurement framework. For more information on all three goals read **"Future Directions for Critical Zone Observatory (CZO) Science" https://criticalzone.org/CZO-FutureDirectionsReport_v3-1.pdf**

CZOs and related research sites

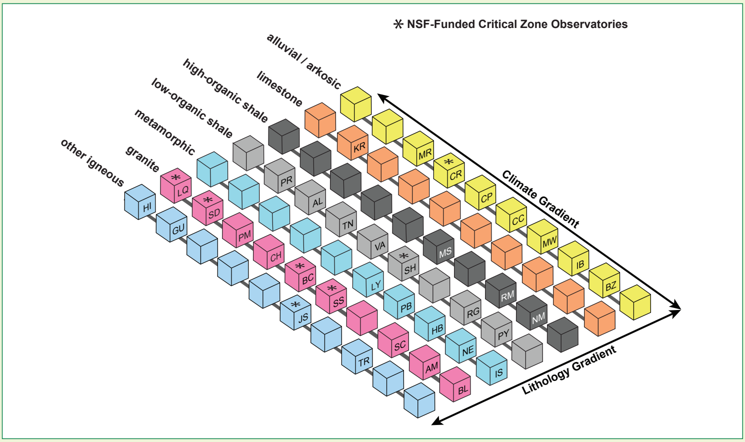
The CZO program in the USA consists of a community of researchers collaboratively working to generate comparable data sets from 6 CZOs spanning a range of differing climatic and physiographic environments in Puerto Rico, Delaware, Pennsylvania, Arizona/New Mexico, Colorado and California.

1. The Boulder Creek CZO (Colorado) focuses on how erosion and weathering control Critical Zone architecture and evolution, concentrating on slope, climate, ecosystems and rock properties.
2. The Christina River Basin CZO (Delaware/Pennsylvania) seeks to integrate knowledge of mineral and carbon cycles to quantify human impact on Critical Zone carbon sequestration from uplands to the coastal zone.
3. The Jemez River and Santa Catalina Mountains CZO (New Mexico/Arizona) focuses on Critical Zone interactions that help drive models of carbon/water cycling, arid/semi-arid ecohydrology, and landscape evolution.
4. The Luquillo CZO (Puerto Rico) studies how Critical Zone processes and water balances differ in landscapes with contrasting bedrock but similar climatic and environmental histories.
5. The Southern Sierra CZO (California) investigates the water cycle and Critical Zone processes, focusing on water balance, nutrient cycling, and weathering across the rain-snow transition.
6. The Susquehanna-Shale Hills CZO (Pennsylvania) emphasizes quantitative prediction of Critical Zone creation and structure, focusing on pathways and rates of water, solutes, and sediments.

International Collaboration

The 6 CZOs primarily work with their European counterpart observatories funded by the European Commission (Soil Transformations in European Catchments or SoilTrEC). These close collaborations have led to shared graduate student/post doc training events hosted by US observatories in 2010 and 2011 and by European partners in 2009, 2012 and 2013. The Shale Hills CZO is a partner on hydrological process studies in the SoilTrEC project. Several USA investigators are members of the SoilTrEC International Advisory Board who participate in annual SoilTrEC meetings, and are actively engaged in developing ties with observatory scientists in France, China, Germany and Australia.

Experimental Design



Reproduced with permission from The Pennsylvania State University with acknowledgement to Chuck Anderson, Sue Brantley and Tim White.

- Schematic diagram of the Critical Zone Exploration Network (www.czen.org) which has the NSF CZO program sites as its core. Sites are arranged along relative climate gradients for each lithology. The U.S.A. Critical Zone Observatories (CZOs, indicated by stars) are: BC = Boulder Creek, CR = Christina River Basin, JS = Jemez River Basin, LQ = Luquillo, SD = Sonoran Desert Environmental Gradient, SS = Southern Sierra and SH = Susquehanna Shale Hills.
- European SoilTrEC sites are: BL = BigLink (Damma Glacier), KR = Koiliaris River Basin, LY = Lysina and PB = Pluhuv Bor.
- USA CZO satellite sites or CZEN seed sites are: AL = Alabama A&M, AM = Adirondack Mountains, BZ = Bonanza Creek, CH = Calhoun Soil-Ecosystem Research and Education Experiment, CP = Central Great Plains, HI = Hawaii, IB = Illinois River Basin, MS = Marcellus shale, MR = Merced River Chronosequence, PM = Panola Mountain, PR = Puerto Rico, RG = Roger's Glen, VA = Washington & Lee, and TN = University of Tennessee.
- SoilTrEC satellite sites are: CC = Clear Creek Observatory and PY = Plynlimon. French sites are: GU = Guadeloupe and SC = Strengbach catchment. Additional sites in the network are: HB = Hubbard Brook Experimental Forest, IS = Integrated Monitoring in Sweden, MW = Muskingum Watershed, NO = Nevada Eco-Hydro-Climatic Observatories (not shown on figure due to large number of sub-sites on differing lithologies), NM = North Ogilvie Mountains, NE = Northeastern Soil Monitoring Cooperative, RM = Richardson Mountains, and TR = Trindle Road Appalachian Trail Diabase.

Key Publications:

Programme Publications Frontiers in Exploration of the Critical Zone: Report of a workshop sponsored by the National Science Foundation (NSF) (PDF) (www.czen.org/files/czen/CZEN_Booklet.pdf); Future Directions for Critical Zone Observatory (CZO) Science (PDF) (http://criticalzone.org/CZO-FutureDirectionsReport_v3-1.pdf)

Publication Lists: see www.criticalzone.org/Publications.html

Text Box 3. Case Study – EC SoilTrEC Project and CZO Network

Web site: www.soiltrec.eu

Funder: European Commission

Research Focus: science evidence to support the EU Thematic Strategy for Soil Protection

Network governance: Large Integrating Project with The University of Sheffield as Coordinating partner

Sixteen partners in Europe, USA and China contribute field sites and expertise for commissioned research. The PI chairs a management committee composed of 8 work package leaders, reporting to the project board with a representative of each partner. An international Advisory Board with independent experts critiques and advises on research progress and plans; there is periodic formal review by the EC and its independent experts.

Research Objectives

The core aim is to develop an integrated model that quantifies soil processes that support food and fibre production; filtering, buffering and transformation of water, nutrients and contaminants; storage of carbon, and biological habitat and gene pool. Objectives are to:

1. Describe from 1st principles soil structure, processes and function at soil profile scale.
2. Establish 4 EU Critical Zone Observatories to study soil processes.
3. Develop an integrated model of soil function within Earth's Critical Zone.
4. Quantify impacts of changing land use and climate on soil functions and value.
5. Create a GIS framework to assess soil threats and mitigation at EU scale.
6. Form with the USA and China a global network of CZOs for soils research.
7. Deliver a programme of public outreach and research transfer on soil sustainability, and
8. Provide effective project management and integration of effort.

Expected Knowledge Advances

- A computational process model at profile and catchment scales that integrate soil erosion, solute transport, nutrient and carbon transformations, and food web dynamics.
- A numerical platform, together with GIS capacity, for a prototype simulator at EU-scale to assess soil threats and evaluate approaches to mitigation.
- Physical-based modelling integrated with new decision support tools from life cycle assessment and ecological economics methodologies.
- A European network of Critical Zone Observatories that describes key stages within the life cycle of soil; its formation, productive use and degradation, with data sets to validate the integrated model of soil processes.
- Integration of process study results with those of additional EU, USA and Chinese field sites to compare soil process rates as they vary more widely with lithology, climate and land use.
- An international training programme via a global network of Critical Zone Observatories.
- A pro-active stakeholder group involved in the practical management of land.

CZOs and related research sites

Four CZOs form the core of the SoilTrEC network of field sites:

1. The Damma Glacier CZO, Switzerland, (BigLink project site), allows the study of incipient soil formation in the glacial forefield as the glacier retreats, exposing the underlying bedrock. A chronosequence on the order of centuries allows the earliest stages of soil formation to be observed.
2. The Fuchsenbigl CZO, Austria, allows the study of soil processes during managed arable land use for production agriculture.
3. The Lysina CZO, Czech Republic, allows the study of soil processes during managed forest land use for intensive silvaculture.
4. The Koiliaris River CZO, Crete, allows the study of highly degraded soils that have experienced millennia of intensive agricultural land use, including grazing, and is under additional threat from desertification due to modern climate change.

Five sites provide additional data sets to test the integrated Critical Zone model against a wider envelope of site conditions and histories:

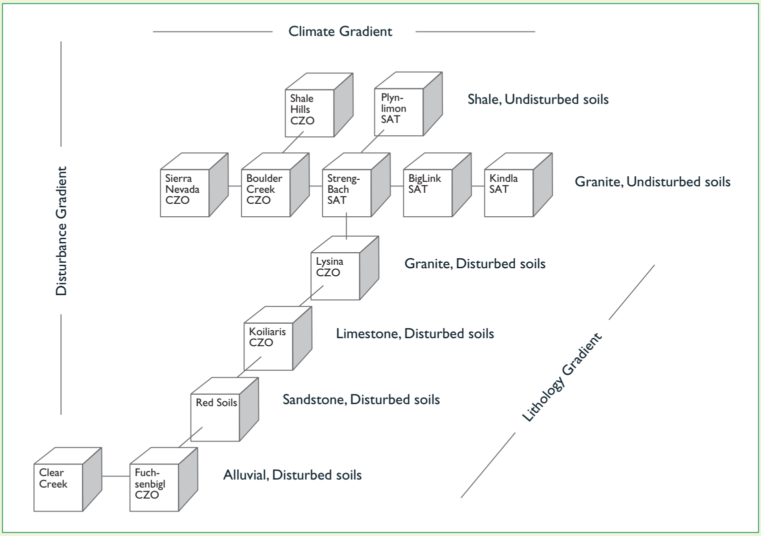
5. Plynlimon Experimental Watershed, UK – pine plantation and grassland, shale lithology.
6. Strengbach Experimental Catchment, France – temperate forest on crystalline lithology.
7. Kindla Integrated Ecosystem Monitoring, Sweden – boreal forest on crystalline lithology.
8. Red Soils CZO, China – sub-tropical mixed agricultural use on sandstone lithology.
9. Shale Hills CZO, USA – temperate forest on shale lithology.

International Collaboration

- Experimental design on global environmental gradients – international workshop Nov '11.
- Red Soils CZO, China hosted international CZO workshop in September 2012.
- Shale Hills CZO, USA – SoilTrEC partner within USA CZO programme.
- Strengbach Experimental Catchment – SoilTrEC partner within French RBV network.
- USA CZOs Boulder Creek and Shale Hills – host joint training events with SoilTrEC.
- Koiliaris and Red Soils CZOs – hosting international training events with USA partners.
- SoilTrEC Data Management Committee – interface with USA partners on data sharing.
- Shale Hills CZO Hydrological modelling team – leads hydrology modelling in SoilTrEC.
- PIs of Boulder Creek, Christina River CZOs in USA – on SoilTrEC Advisory Board.
- TUM CZO, Germany – linked with SoilTrEC, member of German TERENO site network.
- Lysina CZO and Shale Hills CZO – joint drill core (at Lysina) and isotope (at SH) studies.

Experimental Design

4 European CZOs (see above) are located along a conceptual life cycle of soil development and other sites are selected to expand the range of environmental conditions for soil formation along gradients of differing lithology, climate and degree of human disturbance, noted in the diagram below.



Adapted with permission from Banwart et al. (2011).

Key Publications

Banwart, 2011; Banwart et al., 2011; Bernasconi et al., 2011; Balena et al., 2011; Bencoková et al., 2011; Clarke et al., 2011; Farkaš et al., 2011; Fischer et al., 2011; Hindshaw et al., 2011; Krám et al., 2012; Novak et al., 2011; Schomakers et al., 2011; Zhang et al., 2011.

Text Box 4. Case Study – RBV: the French resource for the exploration of the Critical Zone.

Funder: ANR (National Research Agency), CNRS (National Centre for Scientific Research), IRD (Institute for Research and Development), INRA (National Agronomical Research institute), IRSTEA (Institute for Environment and Agriculture Science and Technology) and Universities.

Research Focus

Research and monitoring from the catchment scale to the Amazon Basin scale.

Network governance: RBV is one of the French SOERE « Système d'observation et d'experimentation pour la recherche en environnement », a network of permanent elementary observatories dedicated to the long-term monitoring of Earth's surface.

Each site receives funding from its research institution (CNRS, IRD, INRA, IRSTEA, Universities). RBV is recognised by all French environmental research institutions, funded on a 4-year contract basis by the French Ministry of Research (MESR), and led by a coordinator and a steering committee and evaluated every 5 years. RBV was awarded a 10-year "equipment of excellence" program (CRITEX, CRITical zone equipment program of EXcellence), linking industry and academics and an international scientific committee that will include associate members from US CZOs and SoilTrEC.

Research Objectives

The RBV is a multidisciplinary research community for the study of water and chemical cycles at Earth's surface. Research objectives are diverse depending on land use and land cover conditions.

General objectives of RBV are to:

1. Understand the CZ response to forcings from short-term agricultural to long-term climatic change.
2. Encourage synergistic research between disciplines of the Critical Zone.
3. Foster and stimulate integrated scientific approaches with common measurements in all sites.
4. Build a meta-data base and sharing models.

The aim of the CRITEX program is to develop a shared and centralized instrumental facility including:

1. Equipping selected field sites with innovative instruments.
2. Developing tools to monitor the environment of the Earth at the catchment scale.
3. Developing prototypes of instruments that do not exist.
4. Developing synergistic list approaches between exploration techniques that have not been coupled so far (such as geophysical and geochemical techniques).
5. Novel multidisciplinary approaches that move towards a holistic view of Earth's Critical Zone.

Expected Knowledge Advances

Innovation will include novel sensors and microsensors for soils and rivers to create a step-change in knowledge of flood generation, catchment evaporation and energy budgets, concentration-water discharge relationships in rivers, saturated zone water fluxes, catchment response times to changes in land use, land cover or climate, and soil erosion mechanisms. CRITEX will constrain the processes (across spatial scales) and the energy and matter budgets (i.e. carbon) in catchments, with selected sites to develop a synergistic approach that combines geophysical and geochemical monitoring.

CZOs and related research sites

RBV network includes 15 observatories located in Europe, America, Africa and Asia (Appendix 3).

Hydrometeorological, Hydrological and Erosion Observatories

- OHMCV, 4 sites in Cevennes-Vivarais with regional hydrometeorological observations.
- DRAIX-BLEONE, 7 sites in Hautre Provence with contrasted scales and vegetation patterns.
- AMMA-CATCH, 3 sites in West Africa for monsoon climate and hydrology, semi-arid to humid.

Hydro-biogeochemical Observatories

- HYBAM, 15 sampling stations in Amazon basin, geodynamic, hydrologic and biogeochemical controls on denudation.
- BVET, 2 sites, India, water and biogeochemical cycles in tropical drainage basins.
- ObsErA, 2 sites, Guadeloupe, physical-chemical denudation in volcanic arc and cyclonic climate.
- EroRUN, 1 main site in Réunion, hydrology and biogeochemistry of fast eroding basin on basalt.
- Observatoire de Nouvelle Calédonie, 2 sites, metal fluxes in hydrosystems on ultrabasic rock.

Agro-hydrological Observatories

- AGRYS, 2 sites in Bretagne, contrasting land use to study agricultural and climatic forcing.
- OMERE, 2 sites in France, Tunisia, Mediterranean agro-hydrological responses to global change.
- Oracle, 3 sites Paris Basin at different scales, hydrological and biogeochemical behaviour of hydro-agricultural systems with intensive farming.
- Montoussé, Gers, agricultural impact on biodiversity and water, nutrient and eroson fluxes.
- MSEC, 3 sites in SE Asia, impact of land use changes on erosion and water resources.

Karst Observatories (being integrated into a unique observatory)

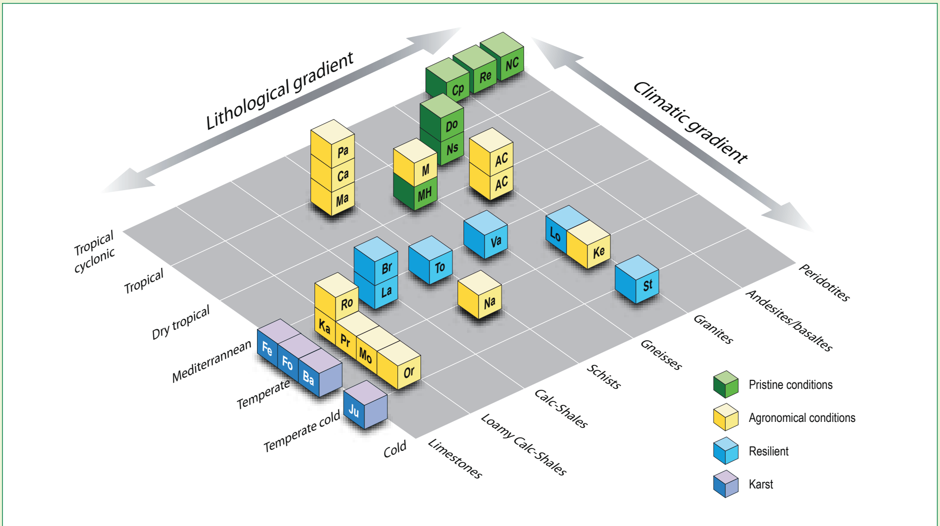
- MEDYCYSS, several deep boreholes sites in Languedoc, monitoring surface and deep waters.
- Jurassic Karst, 5 sites in Jura, geochemical and hydrological altitude gradients.
- Fontaine de Vaucluse-LSBB, Haute Provence, hydrogeological variability on Mediterranean karst.
- SEE Moulis, 3 sites in Pyrénées, hydrogeological variabilty in mountainous karst.

International Collaboration

The RBV collaborates with countries of Africa, South America and Asia, particularly with India, Brazil, Cameroon, Niger, Laos and Vietnam. Several sites of RBV are engaged in scientific collaborations with teams from the US-CZO program (Obsera, Strengbach, Luquillo, Boulder Creek). Exchanges of students and postdocs have permitted common publications. Field campaigns have been initiated. The Strengbach basin, part of the RBV network is also part of the SoilTrEC EC program.

Experimental Design

RBV sites are classified on a lithology vs. climate gradient in the following diagram. Several sites monitor paired basins to compare pristine and anthropogenic conditions. This diagram does not take the climatic or land use heritage into account which has a major role at the catchment scale.



Reproduced with permission from Jerome Gaillardet, Institut de Physique du Globe de Paris.

Key Publications:

Anquetin et al, 2010; Bicalho et al., 2012; Bouchez et al, 2011; Braun et al., 2009; Flechard et al., 2011; Guyot et al., 2009; Jouquet et al., 2010; Lebel et al., 2009; Lloret et al., 2011; Ma et al., 2010; Montreuil et al., 2011; Ruiz let al., 2010; Seghieri et al., 2009.

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

An additional challenge is the translation of knowledge about Critical Zone processes and function into a quantitative description of economic services and other social value 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 environmental change and adapt to it.

ENVIRONMENTAL CHANGE AND THE CRITICAL ZONE IMPACT CHAIN

The DPSIR (Drivers, Pressure, State, Impact, Response; Figure 4) provides a framework to translate new CZ science knowledge into evidence to support policy and management decisions. DPSIR 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. 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 scientists' 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.

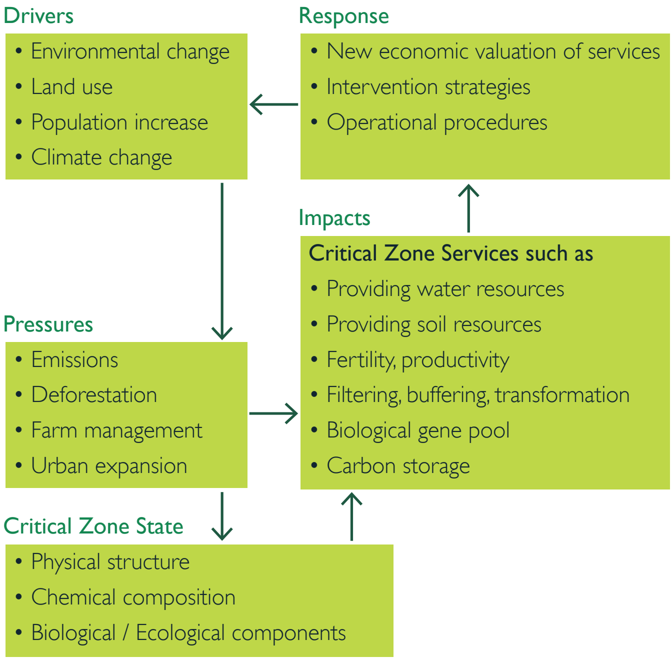


Figure 4. A diagram of the DPSIR framework applied to CZ threats and impacts on CZ Services. Reproduced with permission from Banwart et al. (2012).

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 e.g. accounting for climate, land use, land cover conditions and many other factors, 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.

This capability for Earthcasting, to predict spatial variability and temporal evolution of CZ states, demands a transformative change in international collaboration and in interdisciplinary integration. Plans to enable this were initiated by evaluating the current international capacity for CZO research, prioritising the most urgent science questions to be tackled, and identifying the near- and medium-term steps towards achieving this vision.

Eighty-seven representatives (Appendix 1) from CZOs, and leading independent environmental scientists, from around the world met during 9th-11th November 2011 at The University of Delaware, USA. 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 main 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 by the research groups, and revised and adopted according to the consensus views that emerged. The 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 and paleobiology of the CZ established ecosystem functions and the foundations for CZ sustainability?
2. How do molecular-scale interactions between CZ processes dictate the linkages in flows and transformations of energy, material and genetic information across the vertical extent of above ground vegetation, soils, aquatic systems and regolith - and influence the development of watersheds and aquifers as integrated ecological-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 and its integrated geophysical-geochemical-ecological functions to perturbations such as climate and land use changes, and how can this be quantified by observations and predicted by mathematical modelling of the interconnected physical, chemical and biological processes and their interactions?
5. How can sensing technology, e-infrastructure and modelling be integrated for simulation and forecasting of essential terrestrial variables for water supplies, food production, biodiversity and other major benefits?
6. How can theory, data and mathematical models from the natural- and social- sciences, engineering, and technology, be integrated to simulate, value, and manage Critical Zone goods and services and their benefits to people?

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 and paleobiology of the CZ established ecosystem functions and the foundations for CZ sustainability?

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 climosequences 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 between CZ processes dictate the linkages in flows and transformations of energy, material and genetic information across the vertical extent of above ground vegetation, soils, aquatic systems and regolith - and influence the development of watersheds and aquifers as integrated ecological-geophysical units?

Knowledge Gaps/Research Challenges:

- The nature of interfaces, e.g. at plant/soil, soil/rock, soil/atmosphere and vadose/phreatic zone boundaries.
- The molecular scale interactions operating in the Critical Zone and capability to reproduce them in the laboratory.
- The possibility that genes and organisms allow new reactions and molecular scale interactions, rather than solely accelerate process rates.
- The causes of the heterogeneity of the Critical Zone, both spatially and temporally; e.g. biogeochemical hotspots/hot moments related to heterogeneity in the physical substrate or other underlying causes.
- The effect of brief high intensity events vs. low intensity persistent process rates (frequency, intensity).
- The ability to define state parameters to describe the CZ at the watershed scale; e.g. the value of a thermodynamic model of the watershed or need to incorporate legacy and irreversibility.
- The primary criteria for selecting study sites and monitoring methods; e.g. the challenge of selecting a parameter space (multi-dimensional approach, using lithology, climate, disturbance, land use, legacy, etc.) or a response variation space.

Hypotheses Developed:

- Critical zone function is characterized by diverse processes that we can identify. Laboratory-based data can be scaled to watershed observation (applies for flowpaths, chemistry, biology).
- Each process has a characteristic time and length scale. We can define homogeneous units to define and describe processes.
- CZ architecture and evolution can be predicted from knowledge of initial conditions and forcing (climate, tectonics, lithology) and knowledge of the elementary processes.
- The CZ has emergent properties as we upscale from molecular to watershed level, that long-term observation allows us to identify.
- Upscaling from short to long timescales can be accomplished based on nested observation sequences. There is a window of space and time where we can understand processes over different scales/time.

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 diversity (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.

Soil structure, starting with the internal composition of soil aggregates as building blocks of soil, provides the physical basis for conceptual and mathematical models for upscaling. Within aggregates, molecular interactions between pore fluids and surfaces (mineral, dead organic and biotic) control many processes. These include pore-scale reactive transport; sequestration, transformation and biouptake of nutrients and pollutants, and interparticle forces that create aggregate cohesion or dispersion.

At grain- and larger- scales, soil structure affects fluid permeability and storage, carbon and nutrient dynamics, and habitat to support diverse soil biota. Soil and sediment structure thus provides a unifying framework across the physical dimensions to be addressed. Observations at these scales also dictate a wide range of temporal sampling frequency; from sub-second, real-time data acquisition by in situ sensors, to continuous remote sensing such as satellite observation, and daily-decadal field sampling campaigns.

We need energy, flux and state observations in nested time windows that span process operations to critical zone evolution time scales. Ideally these observations are conducted in a network of sites arrayed along gradients in state parameters; the network should be broadly constructed to incorporate different disciplines. Energy and matter budgets should be feasible.

Each site must be well characterize in terms of architecture and must have a tractable geological/land use/human history. Geophysical monitoring should be encouraged as well as remote sensing coupled to in situ ground sensing. Sensor networking allows us to integrate over large areas.

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 interdisciplinary approach will be possible by virtue of a common scientific language and networked CZO research platform. A subset of CZO's can be identified where specific processes and their dependence on biology, climate/hydrology or other macro-parameters can be calibrated.

The international CZ network should seek to monitor pristine areas if they exist.

Science Question 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?

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.
- A 1-D CZ model that couples biological, physical and chemical processes in order to interpret the legacy of CZ architecture and upscale it to construct the landscape history.

Hypotheses Developed:

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

Experimental Design and Method (or Measurements):

The study of CZ architecture at ridgetops, combined with a coupled 1-D process model will reconstruct the development of CZ architecture in response to the history of tectonic and environmental inputs. This is tractable at individual sites using data from a single borehole and core and current topography. The 1-D model enables intercomparison between many sites worldwide. A minimum of 100 sites, preferably many more, will be selected along gradients of environmental variables. Model development will help identify data needs and aid site selection.

Pre-drilling investigation includes ground survey using shallow geophysics, observations from shallow drilling, and soil analysis. Drilling will proceed to unaltered rock. Drilling techniques will consider the material present; and may use advanced techniques such as sonic drilling that can avoid drilling fluids. In situ characterisation will include downhole observations using techniques such as borehole televiewer and sub-surface geosphysics. Installation of multi-level samplers for sampling groundwater will be used to monitor fluid composition over time at multiple depths.

Drillcore characterisation will include detailed measurements of pore fluid chemistry, mineralogy, mineral chemistry, saturated hydraulic conductivity, cosmogenic nuclides and other isotopic measurements, carbon/microbial biomass, genetic diversity, porosity, moisture content, fracture density/surface area. This data will be combined with other subsurface data including those obtained from the geophysics tools, soil description, pore fluid analyses and other measurements.

The 1-D model will be parameterised using the combined data sets and applied for reconstruction of the development of the CZ architecture over time, evolving from the characteristics of the fresh rock to the present day vertical profile. Intercomparison of sites will be used to test the ability of this approach to interpret CZ architecture across a wide envelope of site histories. Selected sites will be held aside as "blind" sites to assess the capability of the model, parameterized from the previously drilled cores, to predict unknown CZ architecture worldwide.

Future CZO Network:

The CZO network will establish a "Drill the Ridge" campaign to study sequences or gradients of variables that impact CZ architecture and processes. These variables include lithology, climate, channel incision etc. and help to develop a 1-Dimensional CZ process model. In parallel it is necessary to develop a cyberinfrastructure to manage and process the data and to coordinate the modeling efforts. The network will be anchored from established CZOs with transects of drill sites built off of the CZOs. The aim would be populate on the order of 5 climate conditions and 5 landscape erosion rates for each lithology considered. Further sites could include intercomparison between glaciated and non-glaciated terrain, a chronosequences of sites on basalt lithology, and potentially ridges within alluvial material.

Implementation would proceed by bringing together a team of representative from CZOs and additional experts and charge them with scoping the specifications for a model, or suite of models, to describe 1-D evolution of CZ architecture that builds upon the experience of the CZOs. This would identify critical variables and parameters and the criteria for drilling site selection. A central pot of funding would be used to support drilling, with proposals for drilling sites coming in from other field site teams. The network would incorporate universities, smaller colleges and minority-serving institutions situated near drill sites. Multi-lateral international funding would enable inclusion of a wide distribution of site locations worldwide. A dedicated drilling team, e.g. DOSECC would be used to deliver a consistent technical approach to borehole construction and drillcore extraction, and would be used to train CZO personnel worldwide in these specialist methods for ground investigation.

The expected 1-D model would be populated with parameters derived from characteristics of bedrock, climate, variables, erosion and incision rates and hydrologic conditions. From this information it would predict the generalized form of the CZ profile and its chemical characteristics with depth, and it would predict the generalized characteristics of the terrestrial ecosystem, and the present day fluxes of water, energy and major organic and mineral nutrient elements. This outcome would represent an unprecedented transformative capability that links geosciences and ecological sciences for interpretation of the past-, and prediction of future- CZ conditions.

Science Question 4

What controls the resilience, response and recovery of the CZ and its integrated geophysical-geochemical-ecological functions to perturbations such as climate and land use changes, and how can this be quantified by observations and predicted by mathematical modelling of the interconnected physical, chemical and biological processes and their interactions?

Knowledge Gaps/Research Challenges:

- There is a lack of information on thresholds; e.g it is not known how far the CZ system can be stressed before a tipping point is reached.
- The controls on system sensitivity - what can change and what must remain unchanged; e.g. keystone processes/species and causal linkages for key CZ services, and the factors that control the variation in sensitivity in e.g., riparian zones, permafrost, and grasslands.
- Identifying engineering strategies that can be applied to modify, recover or sustain CZ services, e.g. soil fertility.

Hypotheses Developed:

- Most CZ systems have predictable CZ processes and state-dependent responses to perturbation; however some may not and these can be identified.
- 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).
- Resolving these hypotheses and establishing tractable solutions to the challenges requires interdisciplinary investigation; e.g. soil fertility is not solely an agronomic problem, it requires knowledge of site geology and ecology and human behaviour regarding land use and food consumption.

Experimental Design and Method (or Measurements):

Experimental design will include ecology for fully integrated CZO studies. The design is based on establishing site mass and flux balances to understand processes and their role to create or deplete stocks of key CZ components that support ecosystem services. The necessary measurements include climate parameters, energy, water, carbon, nutrient input and output fluxes, biology, food web, hydrology and sediment measurements and ground and airborne geophysical measurements. Site selection will include locations with a downstream lake or impoundment to study the sediment record arising from site fluxes over time.

Future CZO Network:

The CZO network will be selected to systematically characterize anthroposequences of CZ perturbation through land use. Many sites are available worldwide to study specific gradients (e.g. climosequence). Marginal lands being taken into production will be including sites in Africa, Asia and S. America. Integration and collaboration with national monitoring services and public data access by the public are fundamental to establishing the network.

Science Question 5

How can sensing technology, e-infrastructure and modelling be integrated for simulation and forecasting of essential terrestrial variables for water supplies, food production, biodiversity and other major benefits?

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.

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 the natural- and social- sciences, engineering, and technology, be integrated to simulate, value, and manage Critical Zone goods and services and their benefits to people?

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, provides 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) which 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.

INTERNATIONAL AND INTERDISCIPLINARY INTEGRATION

The current scale of international integration of CZ research 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. Specific recommendations were to increase the range of sub-surface geophysical exploration techniques and their deployment at greater depths and a wider range of conditions and sites, also to strengthen the integration with biological and social sciences.

EXPERIMENTAL DESIGN ALONG GLOBAL ENVIRONMENTAL GRADIENTS

Although 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 the need for 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 5).

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. climosequences) 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 observational 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.

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.

Text Box 5. Environmental Gradients for experimental design using networks of CZOs at planetary scale.

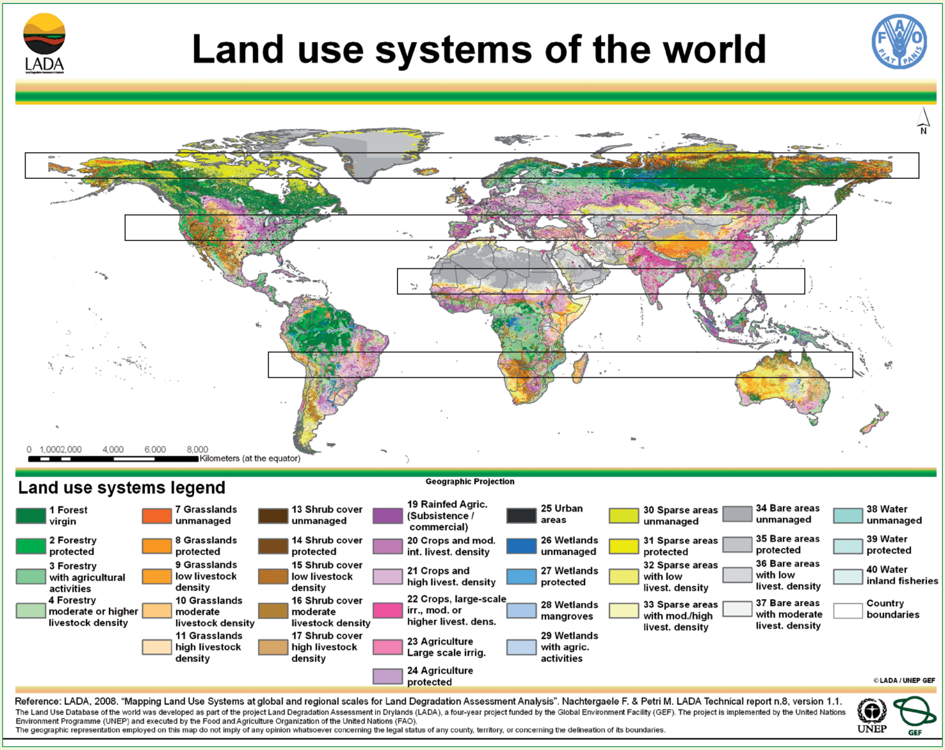


Figure 5a. Global map of land use systems. East-West trending zones of variable land use are marked as boxed areas within broadly similar climate zones. Experimental design includes networks of CZOs located along gradients of land use intensity in these or other zones. CZO data, models and decision tools 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 reproduced with permission from UN Food and Agriculture Organisation, Land Degradation Assessment in Drylands. www.fao.org/nr/lada/

Environmental Gradients for experimental design using networks of CZOs at planetary scale continued on the next page.

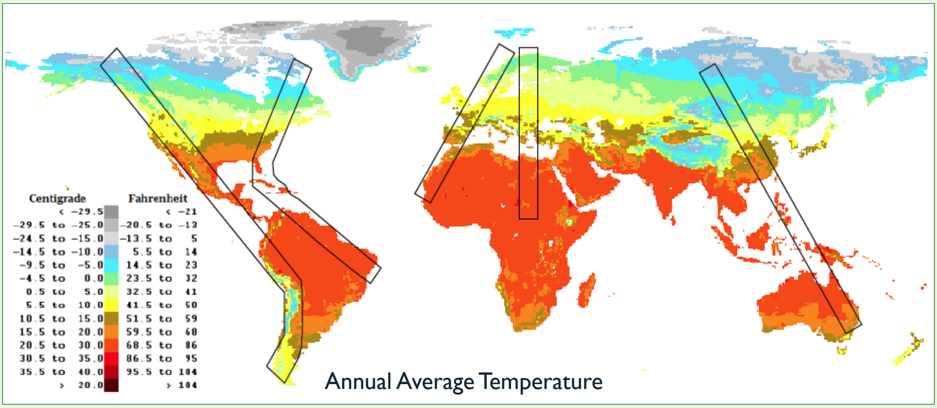


Figure 5b. Global map of average annual temperature with North-South trending climate gradient zones noted as boxed areas. Experimental design can include networks of existing and new CZOs located along the gradients in these or other zones. CZO data, models and decision tools will shed light on the 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. www.climate-charts.com/index.html

MULTILATERAL FUNDING OPPORTUNITIES

Both national and international funding possibilities (including private foundation funding) should be explored for the future CZ research. The new CZO networks 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. An important point of consensus from the workshop participants is that grassroots integration of international CZO research is a major strength but that integration of national funding sources lags behind. The workshop groups agreed that international coordination of funding agencies for a multilateral programme of research is needed for CZ research to fully deliver its potential. Various national science funding agencies, regional (e.g.EU) and private funding sources (e.g. Bill and Melinda Gates 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.

CALL TO ACTION

The science questions and experimental design outlined above lay out an international agenda for CZ science. In order to advance the required international integration, 5 near-term challenges are identified and will be tackled by CZ scientists at current CZOs and additional sites over the coming months. Within 3 years the aim is to have coordinated international funding and governance for a global CZO programme. These actions and the proposed timetable define a project plan to build from existing CZO activities and collaboration – and enable international CZ science to achieve its full potential. Within the next 10 years this is to transform multidisciplinary knowledge, and to discover interdisciplinary solutions, that will sustain Earth's Critical Zone.

1. Creation of a web-based global directory of current and new CZO sites will occur by the end of 2012. 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 was incorporated into SiteSeeker.

2. Wide international dissemination will take place during 2012 and continue, in order to build from these workshop outputs and inform researchers and funders and to progress 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 extending the global research impact of CZOs. A model for governance will be advanced through 2013. This will include consultation with the Earth System Science Partnership (ESSP) composed of 4 Interdisciplinary Bodies (IBs), including the International Geosphere-Biosphere Programme (IGBP), and their common sponsor, the International Council of Science (ICSU). Potential for international CZO research within existing IBs such as the IGBP or as a unique strand of interdisciplinary research will be explored.

3. Vertical integration of CZ processes from above ground ecology to below ground geology, in order to identify the impact linkages such as described by the DPSIR framework (Figure 4) – 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 effort is led by US teams from the national CZO programme and the EarthChem open-source data project (www.earthchem.org).

5. Development of proposals 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 by the NSF and EC CZO projects. 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.

These actions will be further planned, tracked and adapted as needed, within the work and reporting of the existing CZO networks. Plenary discussions on progress and plans for CZOs will be held periodically, coinciding with international conferences. The first opportunity was in September 2012 (Geobiology Conference joint with SoilTrEC Stakeholder meeting, Wuhan, China) with options for future meetings including AGU annual winter meetings, August 2013 (Goldschmidt Conference, Florence, Italy) and June 2014 (Geochemistry of Earth's Surface, France).

REFERENCES

Anderson, S.P., Blum, J., Brantley, S.L., Chadwick, O., Chorover, J., Derry, L.A., Drever, J.I., Hering, J.G., Kirchner, J.W., Kump, L.R., Richter, D. and White, A.F. (2004). Proposed initiative would study Earth's weathering engine. **EOS Transactions, 85**(28), 265-269, American Geophysical Union.

Anquetin, S., Braud, I., Vannier, O., Viallet, P., Boudevillain, B., Creutin, J. D. and Manus, C. (2010). Sensitivity of the hydrological response to the variability of rainfall fields and soils for the Gard 2002 flash-flood event. **Journal of Hydrology, 394**, 134-147.

Balena, S.P., Messerschmidt, I., Tomazoni, J.C., Guimaraes, E. Pereira, B.F., Ponzoni, F.J., Blum, W.E.H. and Mangrich, A.S. (2011). Use of Fe(3+) Ion Probe to Study Intensively Weathered Soils utilizing Electron Paramagnetic Resonance and Optical Spectroscopy. **J. Brazil Chem. Soc., 22**(9), 1788-1794.

Bales, R.C., Hopmans, J., O'Geen, T., Meadows, M., Hartsough, P.C., Kirchner, P., Hunsaker, C.T. and Beaudette D. (2011). Soil moisture response to snowmelt and rainfall a Sierra Nevada mixed-conifer forest. **Vadose Zone Journal, 10** (3) 786-799.

Banwart S.A. (2011). Save Our Soils. **Nature, 474**,151–152.

Banwart, S.C., Bernasconi, S.M., Bloem, J., Blum, W., Brandao, M., Brantley, S., Chabaux, F., Duffy, C., Kram, P., Lair, G., Lundin, L., Nikolaidis, N., Novak, M., Panagos, P., Ragnarsdottir, K.V., Reynolds, B., Rousseva, S., de Ruiter, P., van Gaans, P., van Riemsdijk, W., White, T. and Zhang, B. (2011). Assessing soil processes and function across an international network of Critical Zone Observatories: research hypotheses and experimental design. **Vadose Zone J., 10**, 974–987.

Banwart, S., Menon, M., Bernasconi, S.M., Bloem, J., Blum, W.E.H., de Souza, D.M., Davidsdotir, B., Duffy, C., Lair, G.J., Kram, P., Lamacova, A., Lundin, L., Nikolaidis, N.P., Novak, M., Panagos, P., Ragnarsdottir, K.V., Reynolds, B., Robinson, D., Rousseva, S., de Ruiter, P., van Gaans, P., Weng, L., White, T. and Zhang, B. (2012). Soil processes and functions across an International Network of Critical Zone Observatories: introduction to experimental methods and initial results. Invited contribution to French Academy of Sciences symposium on land erosion and transformation, special issue of **Comptes Rendus Geoscience, 344**, 758-772.

Bencoková, A., Krám, P. and Hruška, J. (2011). Future climate and changes in flow patterns in Czech headwater catchments. **Climate Research, 49**, 1–15.

Bernasconi, S.M., Bauder, A., Bourdon, B., Brunner, I., Bunemann, E., Christl, I., Derungs, N., Edwards, P., Farinotti, D., Frey, B., Frossard, E., Furrer, F., Gierga, M., Göransson, H., Guelland, K., Hagedorn, F., Hajdas, I., Hindshaw, R.S., Ivy-Ochs, S., Jansa, J., Jonas, T., Kiczka, M., Kretzschmar, R., Lemarchand, E., Luster, J., Magnusson, J., Mitchell, E.A.D., Olde Venterink, H., Plötze, M., Reynolds, B.C., Smittenberg, R.H., Stähli, M., Tamburini, F., Tipper, E.T., Wacker, L., Welc, M., Wiederhold, J.G., Zeyer, J., Zimmermann, S. and Zumsteg, A. (2011). Chemical and biological gradients along the Damma Glacier chronosequence, Switzerland. **J. Vadose Zone, 10,** 867-883.

Bicalho, C.C., Batiot-Guilhe, C., Seidel, J.L., Van-Exter, S. and Jourde, H. (2012). Geochemical evidence of water source characterization and hydrodynamic responses in a karst aquifer. **Journal of Hydrology, 450–451,** 206–218.

Bouchez, J., Gaillardet, J., France-Lanord, C., Maurice, L. and Maia, P.D. (2011). Grain-size control of river suspended sediment geochemistry: clues from Amazon River depth-profiles. **Geochemistry, Geophysics, Geosystems, 12**(3), Article Number: Q03008.

Brantley, S.L. (2010). Rock to regolith. **Nature Geoscience, 3**, 305-306.

Brantley, S.L., White, T.S., White, A.F., Sparks, D., Richter, D., Pregitzer, K., Derry, L., Chorover, J., Chadwick, O., April, R., Anderson, S. and Amundson, R. (2006). **Frontiers in Exploration of the Critical Zone, An NSF-sponsored workshop,** 30pp. National Science Foundation, Washington, D.C.

Brantley, S.L., Goldhaber, M.B., and Ragnarsdottir, K.V. (2007). Crossing disciplines and scales to understand the Critical Zone. **Elements, 3**, 315-320.

Braun, J-J., Descloitres, M., Riotte, J., Fleury, S., Barbiero, L., Boeglin, J.L., Violette, A., Lacarce, E., Ruiz, L., Sekhar, M., Kumar, M.S.M., Subramanian, S., and Dupre, B. (2009). Regolith mass balance inferred from combined mineralogical, geochemical and geophysical studies: Mule Hole gneissic watershed, South India. **Geochim. et Cosmochim. Acta, 73**, 935-961.

Clarke, N., Fischer, R., de Vries, W., Lundin, L., Papale, D., Vesala, T., Merilä, P., Matteucci, G., Mirtl, M., Simpson, D. and Paoletti, E. (2011). Availability, accessibility, quality and comparability of monitoring data for European forests for use in air pollution and climate change science. **iForest, 4**, 162-166.

European Commission (2006). **Thematic Strategy for Soil Protection. COM(2006)231**, Commission of the European Communities, Brussels.

Farkaš J., Dejéant A., Novák M. and Jacobsen SB. (2011). Calcium isotope constraints on the uptake and sources of Ca^{2+} in a basepoor forest: A new concept of combining stable (d44/42Ca) and radiogenic (eCa) signals. **Geochimica et Cosmochimica Acta., 75**, 7031-7046

Fischer, R., Aas, W., de Vries, W., Clarke, N., Cudlin, P., Leaver, D., Lundin, L., Matteucci, G., Matyssek, R., Mikkelsen, T.N., Mirtl, M., Öztürk, Y., Papale, N., Potocic, N., Simpson, D., Tuovinen, J-P., Vesala, T., Wieser, G. and Paoletti, E. (2011). Towards a transnational system of supersites for forest monitoring and research in Europe – an overview on present state and future recommendations. **iForest, 4,** 167-171.

Flechard, C.R., Nemitz, E., Smith, R.I., Fowler, D., Vermeulen, A. T., Bleeker, A., Erisman, J. W., Simpson, D., Zhang, L., Tang, Y. S., Sutton, M. A. (2011). Dry deposition of reactive nitrogen to European ecosystems: a comparison of inferential models across the NitroEurope network. **Atmospheric Chemistry and Physics, 11,** 2703-2728.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C. (2010). Food Security: The Challenge of Feeding 9 Billion People. **Science, 327(5937),** 812-818.

Gumiere, S., Raclot, D., Cheviron, B., Davy, G., Louchart, X., Fabre, J-C., Moussa, R. and Le Bissonnais, Y. (2011). MHYDAS-Erosion a distributed single-storm water erosion model for agricultural catchment. **Hydrological Processes, 25**(11), 1717-1728.

Guyot, A., Cohard, J-M., Anquetin, S., Galle, S. and Lloyd, C.R. (2009). Combined analysis of energy and water balances to estimate latent heat flux of a sudanian small catchment. **Journal of Hydrology, 375**(1-2), 227-240.

Hindshaw, R.S., Tipper, E.T., Reynolds, B.C., Lemarchand, E., Wiederhold, J.G., Magnusson, J., Bernasconi, S.M., Kretzschmar, R. and Bourdon, B. (2011). Hydrological control of stream water chemistry in a glacial catchment (Damma Glacier, Switzerland). **Chemical Geology, 285**, 215-230.

Jin, L., Andrews, D.M., Holmes, G.H., Lin, H., and Brantley, S.L. (2011). Opening the "Black Box": Water Chemistry Reveals Hydrological Controls on Weathering in the Susquehanna Shale Hills Critical Zone Observatory. **Vadose Zone Journal, 10,** 928-942.

Jouquet, P., Henry-des-Tureaux, T., Mathieu, J., Thuy, D.T., Toan T.D. and Orange, D. (2010). Utilization of near infrared reflectance spectroscopy (NIRS) to quantify the impact of earthworms on soil and carbon erosion in steep slope ecosystem. A study case in Northern Vietnam. **Catena, 81**, 113-116.

Krám P., Hruška J., and Shanley, J.B. (2011). Streamwater chemistry in three contrasting monolithologic catchments. **Applied Geochemistry, 27**(9), 1854-1863.

Lebel, T., Cappelaere, B., Galle, S., Hanan, N., Kergoat, L., Levis, S., Vieux, B., Descroix, L., Gosset M., Mougin, E., Peugeot, C. and Séguis, L. (2009). The AMMA-CATCH studies in the Sahelian region of West-Africa: an overview. **J. of Hydrology, 375**, 3-13.

Lloret, E., Dessert, C., Gaillardet, J., Alberic, P., Crispi, O., Chaduteau, C. and Benedetti M. F. (2011). Comparison of dissolved inorganic and organic carbon export in the rivers of tropical volcanic island; example from Guadeloupe, French West Indies. **Chem. Geol., 280**, 65-78.

Lin, H. (2010). Earth's critical Zone and hydropedology : concepts, characteristics and advances. **Hydro. Earth Syst. Sci., 14,** 25-45.

Ma, L., Chabaux, F., Pelt, P., Blaes, E., Jin, L., Brantley, S. (2010). Regolith production rates calculated with uranium-series isotopes at Susquehanna/Shale Hills Critical Zone Observatory. **Earth Planet. Sci. Lett., 297**(1-2), 211-225.

MEA (2005). **Ecosystems and Human Well-being: Synthesis. Millennium Ecosystem Assessment,** Island Press, Washington, DC.

Montreuil, O., Cudennec, C. and Merot, P. (2011). Contrasting behaviour of two riparian wetlands in relation to their location in the hydrographic network. **Journal of Hydrology, 406**, 39-53.

National Research Council Committee on Basic Research Opportunities in the Earth Sciences. (2001). **Basic Research Opportunities in the Earth Sciences**. National Academies Press, Washington, D.C.

Novak, M., Zemanova, L., Voldrichova, P., Stepanova, M., Adamova, M., Pacherova, P., Komarek, A., Krachler, M. and Prechova, E. (2011). Experimental Evidence for Mobility/Immobility of Metals in Peat. **Environmental Science and Technology, 45** (17), 7180–7187.

Reid, W.V., Chen, D., Goldfarb, L., Hackmann, H., Lee, Y.T., Mokhele, K., Ostrom, E., Raivio, K., Rockström, J., Schellnhuber, H.J., Whyte, A. (2010). Earth System Science for Global Sustainability: Grand Challenges. **Science, 330(6006),** 916-917.

Richter, D.D. and M. L. Mobley. (2009). Monitoring Earth's Critical Zone. **Science, 326**, 1067-1068.

Ruiz, L., Varma, M.R.R., Mohan Kumar, M.S., Sekhar, M., Maréchal, J.C., Descloitres, M., Riotte, J. and Braun, J-J. (2010). Water balance modelling in tropical watershed under deciduous forest (Mule Hole, India) : Regolith matric storage buffers the groundwater recharge process. **Journal of Hydrology, 380**, 460-472.

Schomakers, J., Mentler, A., Degischer, N., Blum, W.E.H. and Meyer, H. (2011). Measurement of Soil Aggregate Stability Using Low Intensity Ultrasonic Vibration. **SJSS – Spanish Journal of Soil Science, 1**, 8-19.

Seghieri, J., Vescovo, A., Padel, K., Soubie, R., Arjounin, M., Boulain, N., Rosnay (de) P., Galle, S., Gosset, M., Mouctar, A.H., Peugeot, C. and Timouk F. (2009). Relationships between climate, soil moisture and phenology of the woody cover in two sites located along the West African latitudinal gradient. **J. Hydrology, 375**, 78-89.

Vadose Zone Journal, 10(3), 781-987. Special Section: Critical Zone Observatories. (2011).

Zhang, B., Tang, J.L., Gao, Ch. and Zepp, H. (2011). Subsurface lateral flow from hillslope and its contribution to nitrate loading in streams through an agricultural catchment during subtropical rainstorm, events. **Hydrology and Earth System Sciences, 15,** 3153–3170.

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

	Surname	First Name	Institution	Country
1	Anderson	Suzanne	University of Colorado	USA
2	Abrajano	Jun	National Science	USA
3	Alto	Rolf	University of Exeter	UK
4	Andrianaki	Maria	ETH Zurich	Switzerland
5	April	Rich	Colgate University	USA
6	Aruguette	Deborah	National Science Foundation	USA
7	Aufdenkampe	Anthony	Stroud Water Research Centre	USA
8	Bales	Jerad	USGS	USA
9	Banwart	Steven	University of Sheffield	UK
10	Barrera	Enriqueta	National Science Foundation	USA
11	Bernasconi	Stefano	Swiss Federal Institute of Technology	Switzerland
12	Blum	Alex	USGS	USA
13	Brantley	Susan	Penn State University	USA
14	Braun	Jean-Jacques	IRD	France
15	Broadhurst	Amy	University of Delaware/Stroud	USA
16	Brocard	Gilles	University of Pennsylvannia	USA
17	Brooks	Paul	University of Arizona	USA
18	Chabaux	Francois	Centre National de la Recherché Scientfique	France
19	Chadwick	Oliver	University of California, Santa Barbara	USA
20	Chajes	Beth	University of Delaware/Stroud	USA
21	Chorover	Jon	University of Arizona	USA
22	Conklin	Martha	University of California, Merced	USA
23	Cooling	Aisling	University of Sheffield	UK
24	Derry	Lou	Cornell University	USA
25	Dietrich	Bill	Berkeley	USA

	Surname	First Name	Institution	Country
26	Dong	Hailang	Miami of Ohio University	USA
27	Doremus	Kelly	University of Delaware/Stroud	USA
28	D'Ozouville	Noémi	Universite Paris	France
29	Duffy	Chris	Penn State	USA
30	Gaillardet	Jerome	IPG Paris	France
31	Goldhaber	Martin	United States Geological Survey	USA
32	Graham	Wendy	University of Florida	USA
33	Grant	Gordon	Oregon State University	USA
34	Grunwald	Sabina	University of Florida	USA
35	Hardin	Jennifer	USGS	USA
36	Hooper	Rick	CUAHSI	USA
37	Imhoff	Paul	University of Delaware	USA
38	Jerolmack	Douglas	University of Pennsylvannia	USA
39	Jin	Yan	University of Delaware	USA
40	Kaplan	Lou	University of Delaware/Stroud	USA
41	Karwan	Diana	University of Delaware/Stroud	USA
42	Kercheva	Milena	ISSNP	Bulgaria
43	Kram	Pavel	Czech Geological Survey	Czech Republic
44	Kumar	Praveen	University of Illinois	USA
45	Kurtz	Andrew	Boston University	USA
46	Lair	Georg	BOKU	Austria
47	Lazareva	Olesya	University of Delaware/Stroud	USA
48	Lehnert	Kerstin	Columbia University	USA
49	Leopold	Matthias	TUM	Germany
50	Lesmes	David	Department of Energy	USA
51	Lin	Henry	Penn State University	USA
52	Link	Tim	University of Idaho	USA
53	Maher	Kate	Stanford University	USA

	Surname	First Name	Institution	Country
54	McGlynn	Bryan	Montana State University	USA
55	Megonigal	Pat	Smithsonian Institute	USA
56	Menon	Manoj	University of Sheffield	UK
57	Michael	Holly	University of Delaware	USA
58	Miller	Jeanette	University of Delaware	USA
59	Murray	Phil	Rothamsted Research Institute	UK
60	Newbold	Denis	University of Delaware/Stroud	USA
61	Nikolaidis	Nikolaos	Technical University of Crete	Greece
62	Novak	Martin	Czech Geological Survey	Czech Republic
63	Packman	Aaron	Northwestern University	USA
64	Pan	Genxing	Institute of Resources, Ecosystem and Environment for Agriculture, Nanjing	China
65	Panagos	Panos	EC-JRC	Italy
66	Papuga	Shirley	University of Arizona	USA
67	Peltre	Clement	University of Pennsylvannia	USA
68	Phillips	Fred	New Mexico Tech	USA
69	Pizzuto	Jim	University of Delaware	USA
70	Powell	Heather	National Ecological Observatory Network	USA
71	Ragnarsdottir	Vala	University of Iceland	Iceland
72	Riebe	Cliff	University of Wyoming	USA
73	Roering	Josh	University of Oregon	USA
74	Rosier	Carl	University of Delaware/Stroud	USA
75	Rowlings	David	Queensland University of Technology	Australia
76	Scatina	Fred	University of Pennsylvannia	USA
77	Schwartz	Egbert	North Arizona University	USA
78	Soloman	Kip	University of Utah	USA
79	Sparks	Don	University of Delaware	USA
80	Thompson	Aaron	University of Georgia	USA

	Surname	First Name	Institution	Country
81	van Gaans	Pauline	Deltares	Netherlands
82	Völkel	Jörg	TUM/TERENO	Germany
83	White	Tim	Penn State	USA
84	Williams	Jennifer	Penn State University	USA
85	Wilson	Cathy	Los Alamos National Lab	USA
86	Yoo	Kyungsoo	University of Minnesota	USA
87	Zhang	Bin	Institute of Agricultural Resources and Regional Planning	China

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., 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, N., 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., 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 Scientifique
9	Development of a Global Geochemical Database for CZEN Applications	Niu, X., Williams, J., Jin, L., Brantley, S.	Penn State University
10	Dynamics of tropical ecosystems in context of global changes (climatic variations/human activities)	Braun, J-J.	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

	Poster Title	Authors	Institution
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., Probst, A.	Centre National de la Recherché Scientifique
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., Krám, P.	Czech Geological Survey
17	Monitoring of the Kabini watershed	Braun, J-J.	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., 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 – CZO	Nikolaidis, N., Efstathiou D.	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., 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

	Poster Title	Authors	Institution
26	Susquehanna/Shale Hills Critical Zone Observatory	Duffy, C., Brantley, S., Davis, K., Eissenstat, 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., Hawkins, J.	Rothamsted 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., Mitra, B.	University of Arizona
39	Watershed Characterization & hydrological functioning (Mule Hole, Forested)	Braun, J-J.	IRD – Institut de Researche pour le development

	Poster Title	Authors	Institution
40	Weathering of the biogeochemical cycles (Mule Hole & gradient)	Braun, J-J.	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

	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 France	Languedoc and Cap Bon (two sites)	France and Tunisia
45	ORACLE	Brie, Paris Basin	France
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	Merced, CA	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
61	Beacon Farm	Rakaia River catchment, Canterbury Plains	New Zealand
62	Omere site	Northern Tunisia	Tunisia

Sustaining Earth's Critical Zone
Basic Science and Interdisciplinary Solutions for Global Challenges

ISBN: 978-0-9576890-0-8