Chapter 2

The Role of Critical Zone Observatories in Critical Zone Science

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2.1 THE CRITICAL ZONE

The Critical Zone (CZ), a term first coined by the US National Research Council (2001), encompasses the thin outer veneer of Earth's surface extending from the top of the vegetation canopy down to the subsurface depths of fresh groundwater. Complex biogeochemical-physical processes combine in the CZ to transform rock and biomass into soil that in turn supports much of the terrestrial biosphere. Processes in the Critical Zone are represented by coupled physical, biological, and chemical processes (Fig. 2.1), and scientific expertise from an array of disciplines is needed to understand the zone and its processes: geology, soil science, biology, ecology, geochemistry, hydrology, geomorphology, atmospheric science, and many more. The zone sustains most aboveground terrestrial life including humanity. Yet, the science of coupled human-natural systems is far

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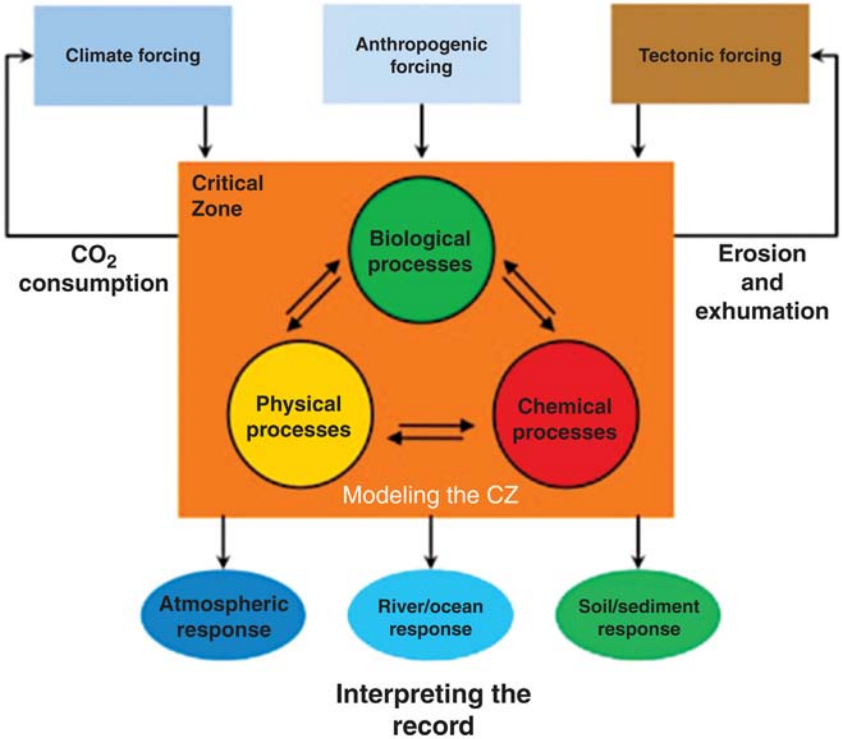

FIGURE 2.1 Physical, chemical, and biological processes in the Critical Zone (CZ) are subjected to climate, tectonic, and anthropogenic forcing that lead to responses in the atmosphere, biosphere, hydrosphere, lithosphere, and pedosphere. The challenge of CZ science is to interpret CZ processes over both short and long timescales: for example, CZ scientists attempt to understand sediment and soil records for comparison to changes in the CZ associated with ongoing climate and land-use change. *(From Brantley et al. (2007).)*

from developing a theory that could offer the potential to predict, or earthcast, the environment of the future (e.g., Godderis and Brantley, 2014), not to mention one that could yield the knowledge needed to slow or reverse environmental degradation in a sustainable fashion (National Research Council, 2010).

The structure and functioning of the CZ have evolved in response to climatic and tectonic perturbations throughout Earth's history with the processes driving change more recently accelerated by human activities in the Anthropocene (e.g., Vitousek et al., 1996; Wilkinson, 2005; Steffen et al., 2007; see Fig. 2.2). The degraded state of Earth's surface has been well documented, for example, in the United Nations Environment Programme's (UNEP) Millennium Ecosystem Assessment report (2005), http://www.unep.org/maweb/en/index.aspx, and UNEP (2005), One Planet Many People: Atlas of Our Changing Environment (2005); the Intergovernmental Panel on Climate Change Fifth Assessment Report, http://www.ipcc.ch/; Smith (2012), Penguin State of the World Atlas: Ninth Edition (2012); and Hoekstra et al. (2010), The Atlas of Global Conservation: Changes, Challenges, and Opportunities to Make a Difference.

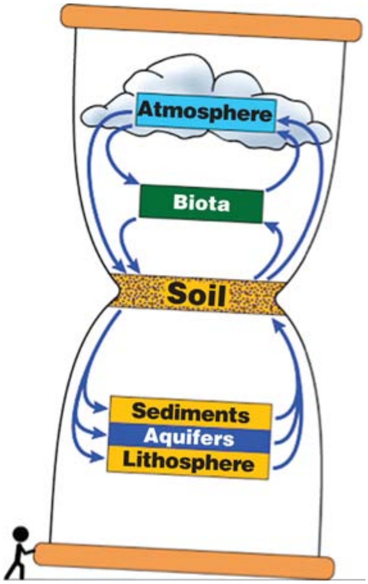

FIGURE 2.2 The Critical Zone Observatory mission is to learn to: measure the fluxes occurring today, read the geological record of the cumulative effect of these fluxes through time, and develop quantitative models of CZ evolution. By measuring what is happening today and reading what happened yesterday, we will learn to project what will happen tomorrow – including humanity's role. *(From Godderis and Brantley (2014).)*

Hooke et al. (2012) summed up some of the topics and tone of these reports, concluding that humans have modified more than half of Earth's land surface, that the current rate of land transformation is unsustainable, and that "changes that human activities have wrought in Earth's life support system have worried many people." To many scientists and citizens, these threats to this essential component, that is, the CZ, of our life-support system, have reached an acute level, yet the science of understanding and managing these threats mostly still remains embedded within individual disciplines, and the science has largely remained qualitative – never has a more important time occurred for an international interdisciplinary approach to accelerate our understanding of processes in the CZ and how to intervene positively to mitigate threats and ensure CZ function. The immediate challenge is to develop a robust predictive ability for how the CZ attributes, processes, and outputs will respond to projected climate and land-use changes to guide societal adaptations toward a more sustainable future. This predictive ability must be founded on a sufficiently broad knowledge of the CZ system and CZ processes to describe the interactions of the varied climatic, ecologic and geologic factors that distinguish different geographic regions – a primary focus of the scientific and educational efforts at Critical Zone Observatories (CZOs). The aim of the US CZO program is largely focused on developing methods to quantitatively project the dynamics of Earth surface processes – from the past, through today into the future.

The key to CZ science is to use observatories as time telescopes that allow focus, not only on the processes and fluxes operating today, but to compare these to the record of the processes in the rock and soil and sediment record – then to use quantitative models parameterized from these observations across scales of space and time to project the future using various scenarios of human behavior. One example of forward-projecting CZ science is shown in papers investigating the record of change in a soil climosequence along the Mississippi River in the United States. (Williams et al., 2010) using climate models to drive soil-development models (Godderis et al., 2010) that are in turn used to project the future of the soils and water (Godderis et al., 2013). By implementing such an approach at CZOs where datasets are less sparse, we will learn how mass and energy fluxes interact with biota and lithology over geological timescales, transforming bedrock into soils. We will also learn how the same, coupled processes enact feedbacks between the CZ, changing climate and land use over timescales of human decision-making. Furthermore, while the example focuses on weathering, many other CZ processes can be similarly addressed.

2.2 CRITICAL ZONE OBSERVATORIES (CZOs)

CZOs are natural watershed laboratories for investigating Earth-surface processes mediated by fresh water. Research at the CZO scale seeks to understand these little-known coupled processes through monitoring of streams, climate/weather, and groundwater. CZOs are instrumented for hydrogeochemical measurements and are sampled for soil, canopy, and bedrock materials. CZOs involve teams of cross-disciplinary scientists whose research is motivated and implemented by both field and theoretical approaches, and include substantial education and outreach.

The interdisciplinary and integrative science of the CZOs is a relatively new scientific endeavor formalized through the US NSF funding of the CZO program. The US CZOs were chosen through a rigorous NSF peer review process, based on standard NSF criteria. A CZO National Office (CZONO) is now in place to guide network-level activities. Details of the US CZO program and each of the 10 observatories (described later) may be found at: http://criticalzone.org/.

The CZOs – whether funded by the US NSF, the European Commission or similar entities in France, Germany, Australia, China, or other nations – uniquely address the challenge of understanding terrestrial life's support system. Of all the environmental observatories and networks, the CZOs are the only ones to tightly integrate ecological and geological sciences to combine with computational simulation, and to project from the deep geologic past to that of human life spans. As such, CZOs represent a unique opportunity to transform our understanding of coupled surface Earth processes and to address quantitatively the impacts of climate and land use change and the value of Critical Zone functions and services. Indeed, a fundamental concept applied from ecological economics is that the CZ embodies natural capital as a means of production to support flows of materials, energy, genetic information, and human population over time.

Although all the observatories worldwide are not called CZOs, many of the scientists worldwide use the energizing framework and nomenclature of "Critical Zone science" in their strategies of national science. This is because CZOs provide essential data sets and a coordinated community of researchers that integrate hydrological, ecological, geochemical, and geomorphic-process science from grain to watershed scales and, perhaps as importantly, from deep time to human timescales. Furthermore, scientists in each country have found the paradigm of CZ science to be compelling in addressing problems and attracting students to the field. Nonetheless, each national program has its own approach and strategy. For example, European CZOs are integrated with social sciences related to ecological economics and management science in order to translate natural science advances into European Union policy. CZOs are the lenses through which understanding will be gained of the complexity of interactions between the lithosphere, the hydrosphere, the biosphere, the atmosphere, and the pedosphere through time.

The NSF CZO program began in 2007 with support of the Susquehanna-Shale Hills Observatory in Pennsylvania, the Southern Sierra Observatory in California, and the Boulder Creek Observatory in Colorado. In 2009, three additional observatories were added to the program: Luquillo Mountains Observatory in Puerto Rico; Christina River Basin CZO in Delaware and Pennsylvania; and the Jemez River Basin/Santa Catalina Mountains CZO in Arizona and New Mexico. Most recently, four new observatories were selected for funding: Eel River CZO in northern California; Reynolds Creek CZO in Idaho; the Intensively Managed Landscape CZO in Illinois, Iowa and Minnesota, and the Calhoun Forest CZO in northern South Carolina (Fig. 2.3). The following descriptions of each US CZO are chronologically organized based on the timing of funding from the NSF and hence their formal designation as a US CZO.

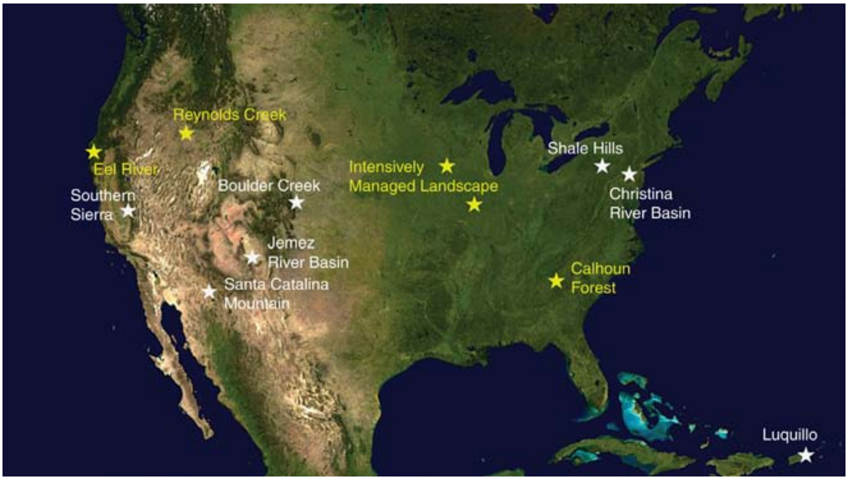

FIGURE 2.3 The United States CZO network consists of seven sites developed since 2007 (two linked as one CZO in NM and AZ) shown in white, with an additional four sites recently designated in 2014 (light gray [yellow in the web version]).

2.2.1 The First Observatories (2007)

2.2.1.1 Boulder Creek (BcCZO)

The BcCZO is situated in the Colorado Front Range, one of the Laramide ranges. Boulder Creek flows east, from the Continental Divide to the eastern Great Plains (Fig. 2.4), crossing landscapes shaped by glaciers and permafrost, fluvial canyon incision, and exhumation of the former Cretaceous seaway sedimentary rocks on the Great Plains (Murphy, 2006).

The BcCZO team focuses on three catchments within the greater Boulder Creek watershed (Fig. 2.5). Betasso, at an elevation of 1810–2024 m, is underlain by Precambrian granodiorite (GD) in lower Boulder Canyon. Its steep ephemeral stream cascades into Boulder Canyon from a low relief upland. Grasses and Ponderosa pine dominate vegetation. Mean annual precipitation is ~400 mm, of which 60% falls as snow. Gordon Gulch (2440–2740 m) is on the low relief Rocky Mountain surface, underlain by Precambrian biotitic gneiss. Long evolution, notably including past periglacial conditions (Leopold et al., 2014), shaped this landscape. Different aspect slopes present contrasts in regolith and vegetation: thinner, less-weathered regolith with grasses and Ponderosa pine exists on south-facing slopes, whereas thicker, more weathered regolith with dense Lodge pole pine exists on north-facing slopes (Befus et al., 2011; Anderson et al., 2014). Mean annual precipitation here is ~500 mm, of which 70% falls as snow. Green Lakes valley (3560–4020 m) is a glaciated alpine watershed on Precambrian biotitic gneiss and GD. As part of the Niwot Ridge

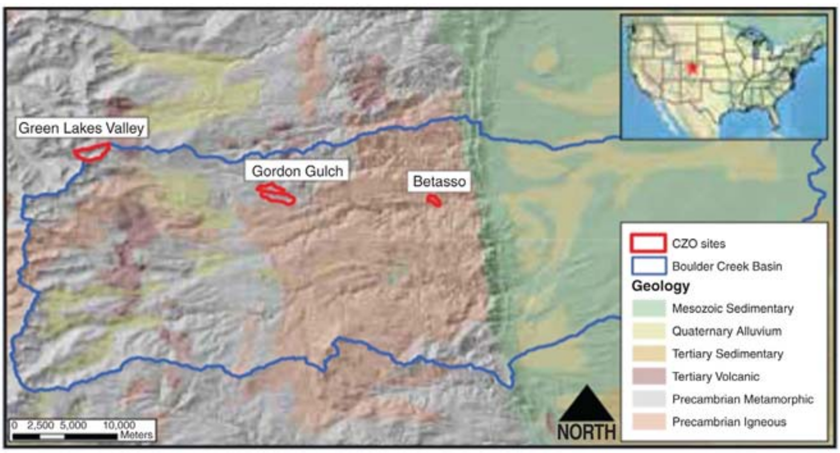

FIGURE 2.4 Map of Boulder Creek watershed (light gray outline [blue outline in the web version]); inset shows location in the USA. The watershed crosses crystalline rocks from the alpine Continental Divide (~4100 m) on the west, and through the forested Rocky Mountain surface (~2000–2700 m). The eastern half of the watershed drains grasslands of the Great Plains (~1480 m) underlain by Mesozoic sedimentary rocks (chiefly shale). Three instrumented subcatchments (dark gray outline [red outline in the web version]) represent different vegetation, climate, and erosional histories.

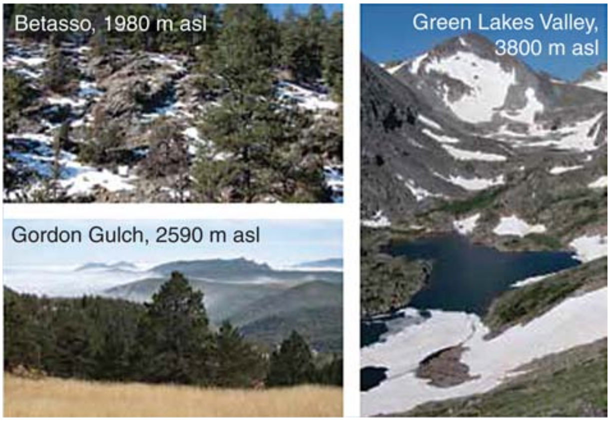

FIGURE 2.5 Vegetation, topography, and climate vary in each instrumented catchment in BcCZO. Green Lakes valley is above tree line, and its precipitation is dominated by snow. Gordon Gulch is below the glacier limit on the rolling terrain of the Rocky Mountain surface. It is forested, and has strongly contrasting north and south-facing slopes. Betasso stretches from the bottom of the bedrock-dominated Boulder Canyon, up to the gentler Rocky Mountain surface in a forested area of ephemeral streams and ephemeral snow.

LTER, monitoring data extends back several decades (e.g., Caine, 2010). Mean annual precipitation is ~1200 mm, of which 85% falls as snow.

Research infrastructure in the CZO includes meteorological stations at Betasso and Gordon Gulch, soil-temperature and soil-moisture probes at multiple depths within soil profiles at all locations, arrays of soil water samplers (zero tension, ceramic and fused quartz suction lysimeters) at Gordon Gulch, automated, snow-depth sensors at all locations, time-lapse cameras at Gordon Gulch and Green Lakes Valley, stream gauges at all locations, automated, stream-water samplers at Gordon Gulch, manual, surface-water and snow-sampling program at all locations, and groundwater wells at Betasso and Gordon Gulch. The BcCZO team engages substantially in community outreach and education, including a partnership with the University of Colorado's Science Discovery to bring CZ science to K-12 students and teachers, summer classes entitled "Go with the flow" and "Fire and ice," middle school "Science Explorers" workshops, a high-school experience with mountain research, and a field course for professional development of Colorado teachers (http://www.colorado.edu/sciencedisovery/).

The BcCZO science team aims to understand how Critical Zone architecture evolves over time (Anderson et al., 2012), how it conditions hydrologic and biogeochemical response and ecosystem structure (Eilers et al., 2012; Gabor et al., 2014; Hinckley et al., 2014b), and how it will respond to future changes in climate (Fig. 2.6). These goals are addressed by documenting CZ architecture, denudation processes and rates; studying weathering-front advance and hydro-biogeochemical coupling; and through modeling these systems.

Key research highlights to date include understanding of the: (1) Critical Zone role in exhumation of the Plains (Wobus et al., 2010). Cosmogenic radionuclide

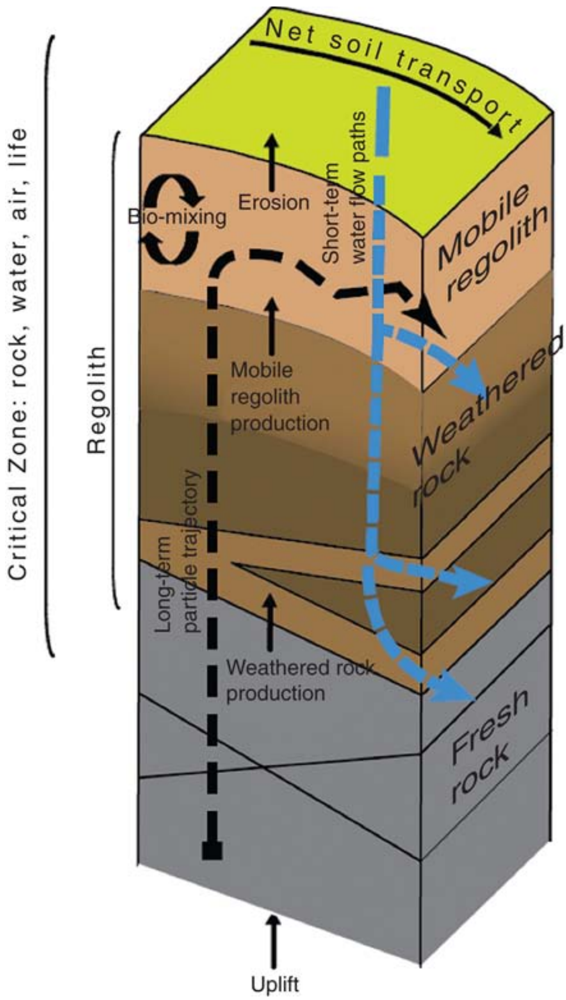

FIGURE 2.6 A schematic diagram of Critical Zone architecture displaying typical layering of mobile regolith, weathered rock and fresh rock, and the flow paths of water (chiefly downward), and trajectories of parcels of rock (vertically up, until it reaches the bio-mixing zone of the mobile regolith layer). *(Figure modified from Anderson et al. (2007).)*

ages of strath terrace sediment covers on the Plains suggest that terrace planation occurs during glacial episodes, and river incision during deep interglacial episodes (Dühnforth et al., 2012). This further indicates that change in sediment delivery from hill slopes (Anderson et al., 2013) is a key driver of river down cutting, which itself incites transient adjustment of hill slopes. (2) Slope aspect provides insight into controls on weathering front advance and slope processes (Anderson et al., 2014). At the rain–snow transition, aspect strongly controls snowpack presence, which controls water delivery (Hinckley et al., 2014a). The thickness of weathered rock varies with slope aspect as well (Befus et al., 2011), which could reflect these differences in water flow path or some other process difference over the order of 10^5 years residence time in the weathered rock layers. (3) Multiple roles of trees. In addition to sediment transport by tree fall, trees also stress rock and transport regolith, simply by growing and dying. Over the lifetime of a tree (on the order of 100 years), rock and regolith are dilated and collapse; roots act as slow explosions, breaking and prying apart rock (Hoffman and Anderson, 2014). (4) Hydraulic conductivity and porosity structure of the Critical Zone controls water flow, with feedbacks on the evolution of structure within ecosystems and rock porosity (Gabor et al., 2014). For example, the decline in porosity with depth leads to the potential for threshold-like behavior in water delivery to rocks and for strong lateral flow even in the vadose zone (Langston et al., 2011).

2.2.1.2 Southern Sierra

The Southern Sierra Critical Zone Observatory (SSCZO) was established in 2007 as a community platform for research on Critical Zone processes, and is based on a strategic partnership between the University of California and the Pacific Southwest Research Station (PSW) of the US Forest Service. The SSCZO is co-located with PSW's Kings River Experimental Watersheds (KREW), a watershed-level, integrated ecosystem project established in 2002 for long-term research to inform forest management. The SSCZO is built on a transect of instrumented sites at elevations from 400 m to 2700 m, anchored by the oldest site in a productive mixed-conifer forest at the rain–snow transition (1750–2100 m) (Fig. 2.7). The main SSCZO site includes three headwater catchments with a dominant southwest aspect (Fig. 2.8).

Soils within the Providence watersheds developed from residuum and colluvium of granite, GD, and quartz diorite parent material. Soils are weakly developed as a result of the parent material's resistance to chemical weathering and cool temperatures. Upper-elevation soils are at the lower extent of late Pleistocene glaciations. Shaver and Gerle–Cagwin soil families dominate the watershed. Soils are gravely sand to loamy sand, with a sand fraction of about 0.75. Soils are shallow (<50 cm) in parts of the watershed, with low tree density and many rock outcrops. Soils in more gently sloping terrain with linear or convex hill slopes are moderately deep; and landforms with the deepest soils (>150 cm) support a high tree density.

The area has a high forest density, with canopy closures up to 90%. PSW plans to thin and/or carry out controlled burns in two of the three-headwater catchments as part of the KREW study, to inform forest managers about impacts of thinning on ecosystem services.

The southern Sierra Nevada is a Mediterranean climate, and experiences relatively wet winters and dry summers. Annual average temperatures are about 8°C at the bottom and 1–2°C cooler at the top of the SSCZO catchments, differences that are driven largely by daytime temperatures and cold-air drainage at night. Daytime winds are upslope and nighttime winds downslope, with wind speeds generally under 1–2 m/s. Precipitation averages about 120 cm per year, and is about 20–60% snow. Photosynthesis persists through the winter, and

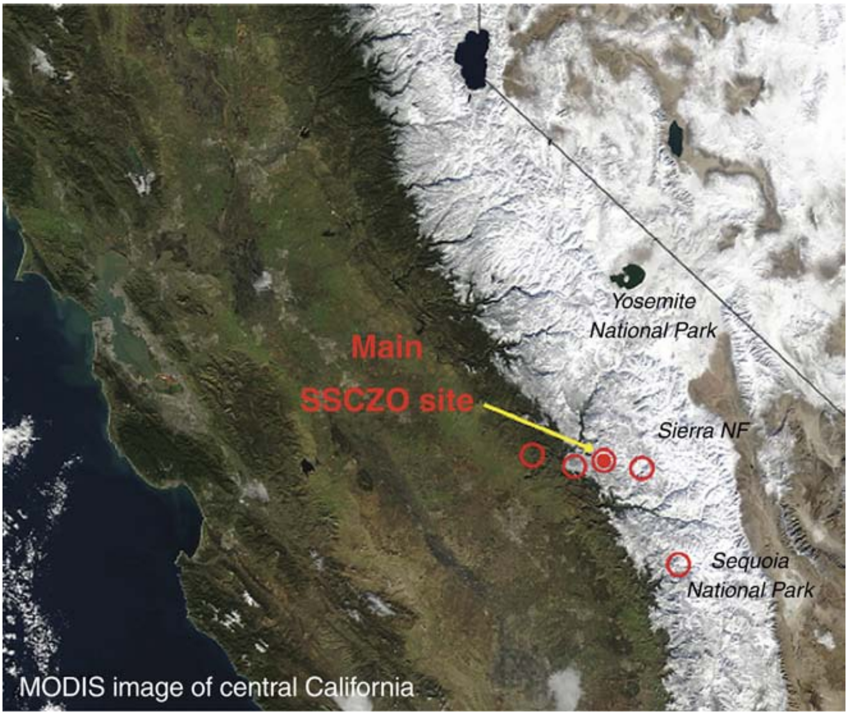

FIGURE 2.7 The Southern Sierra CZO spans an elevation gradient from 400 m to 2700 m. Oak–pine woodlands dominate the lowest elevations, middle elevation sites are in mixed conifer forest, and the highest elevations lie in subalpine forest.

soils and regolith store enough water for photosynthesis to occur all summer. As soils dry out, trees apparently extract water from the deeper soils. Annual runoff is about 15–30% of precipitation in dry years, increasing to 30–50% in wet years. The ground is snow covered for 4–5 months each year, and may experience multiple melt events during the winter and spring (Fig. 2.9).

Two meteorological stations exist, a 60-m flux tower, a 60-node wireless embedded sensor network, 215 EC-TM sensors for volumetric water content, over 110 MPS sensors for matric potential, 60 snow-depth sensors, meadow piezometers and wells, sap-flow sensors, stream gauges and water-quality measurements.

Level 2 data (cleaned, calibrated) from core field measurements are made available by water year. These include precipitation, energy balance, snow, stream flow, soil moisture, sap flow, temperatures, stream geochemistry, soil chemistry, flux-tower data, meadow water levels, vegetation, and various other characterization data sets. Raw data are posted as it is collected. Current-year level-1 data are available by request. Investigator-specific data are available as per the NSF data policy. The area has multiple LIDAR coverage, and a variety of other data sets are available through PSW scientists. It is planned to locate NEON flux towers within the current elevation transect of four SSCZO towers.

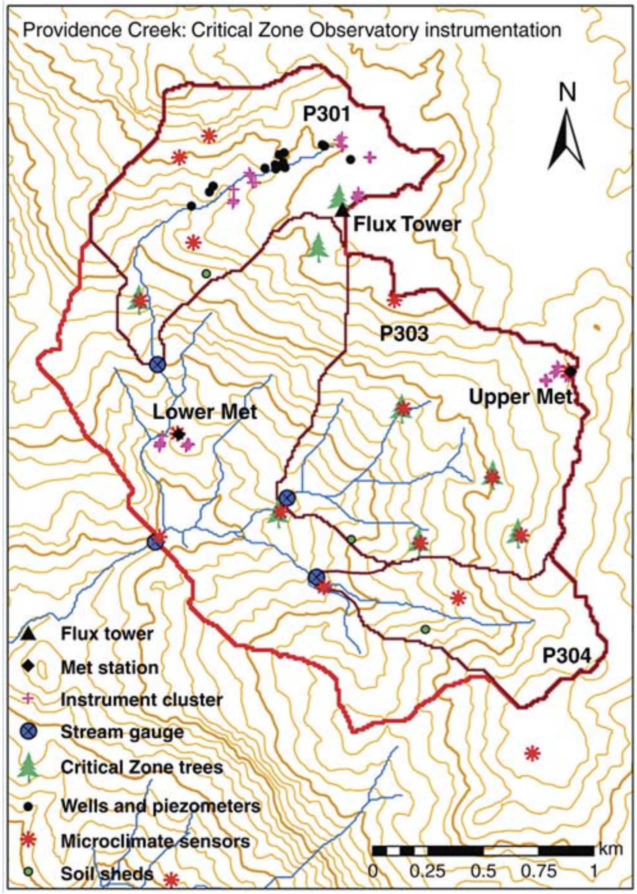

FIGURE 2.8 The most heavily instrumented site is at Providence Creek (1700–2000 m in elevation). This site is also part of the Forest Service KREW (Kings River Experimental Watershed) project. The map shows instrumentation at the site by the Southern Sierra CZO and KREW.

The conceptual science model for the SSCZO is built around bi-directional links between landscape/climate variability and water/material fluxes across the rain–snow transition. Ongoing research focuses on water balance, nutrient cycling and weathering across the rain–snow transition; soil moisture is an integrating variable. Science questions currently being addressed include: (1) How landscape variability controls? How soil moisture, evapotranspiration, and stream flow respond to snowmelt and rainfall? (2) How soil moisture is linked to topographic variability, soil formation and weathering? (3) What physiological mechanisms are controlling how vegetation distribution and function vary with climate? (4) How vegetation attributes influence cycling of water, energy, and CO_2? (5) What links occur between soil heterogeneity, water fluxes and nutrient availability?

FIGURE 2.9 The road into the P301 subcatchment climbs a rise to 2000 m. Snow can persist into June, or melt out in March at this site. Daily photos taken near this point at the site (at Critical Zone Tree-1) show intermittent snow cover with multiple melt events in some winters.

Ecosystem types. The mid-elevation Providence catchments are largely Sierra mixed-conifer forest, with some mixed chaparral and rock outcrops. Dominant trees are white fir, ponderosa pine, Jeffrey pine, sugar pine, incense cedar and black oak. Several species of shrubs are also present. Of the three perennial streams, one borders meadow over 90% of its length, one has no meadow, and the third is intermediate. The lowest elevation site (400 m) is located at the San Joaquin Experimental Range. This site has oak-pine woodlands and annual grasses. The mixed-conifer forest of the lower mid-elevation site (1160 m) is dominated by ponderosa pine and black oak. Subalpine Lodge pole pine forests cover the highest elevation site (2700 m).

Research highlights. The distributed snow and soil moisture measurements show a close coupling between snowmelt and soil drying in spring/summer, with systematic variability across elevation, aspect and canopy cover. Evapotranspiration (ET) decreased proportionally as soils dried, going from about 1 mm/d to 0.1 mm/d over the summer. However, about half of the ET occurred after snow melted. Runoff increased with elevation, corresponding to decreasing temperature, more precipitation falling as snow, decreasing vegetation density and coarser soils. Nutrient hotspots in soils are important for nitrogen cycling, and do not necessarily correspond to preferential flow paths for water. Annual erosion rates measured in headwater catchments are only 1% of long-term rates, with head cut and bank erosion dominating. Sensor networks that are wireless and embedded statistically sample the landscape variability and have proven to be an economical, scalable approach to measurement design; this approach is being replicated at other locations in the Sierra Nevada.

2.2.1.3 Shale Hills

The focus of the SSHCZO is the Shale Hills watershed (red square on Fig. 2.10), an 8 hectare catchment which lies within the Valley and Ridge physiographic province of the central Appalachian Mountains in Huntingdon County, Pennsylvania (40°39′52.39″N 77°54′24.23″W) (Lin, 2006). It is a first order, V-shaped basin characterized by relatively steep slopes (25–35%) and narrow ridges. The stream is a tributary of Shavers Creek that eventually debauches into the Juniata River, a part of the Susquehanna River Basin. Since 2013, the focus of SSHCZO has grown to include sites within the larger Shavers Creek watershed (Fig. 2.10), including a small, forested satellite catchment located on sandstone

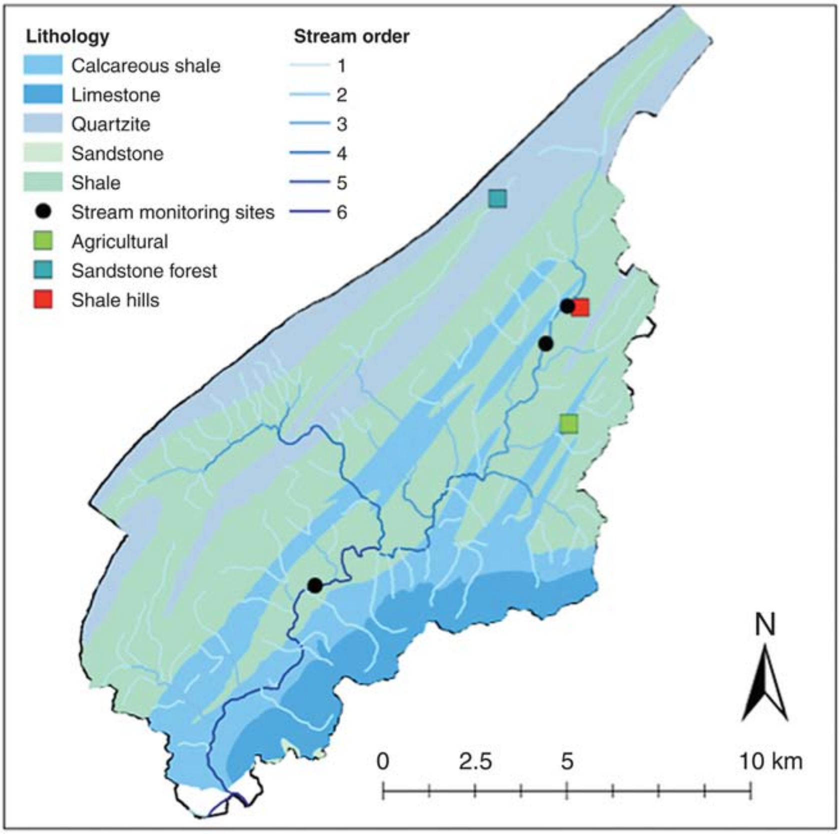

FIGURE 2.10 Geological map of the Shavers Creek Watershed in central PA. Shale Hills (darkest gray square [red square in the web version]) is the original focus of the CZO. New stream monitoring sites (black circles) have been established on the main stem of the Creek, and two new subcatchments (two lighter gray squares) are being implemented as shown.

(blue symbol). The CZO will eventually include a similarly sized agricultural catchment on calcareous shale (green symbol). Study of the small catchments is a step toward scaling up to the entire Shavers Creek watershed. Outreach to watersheds in northern PA that are impacted by shale-gas development is also ongoing.

The Shale Hills catchment is oriented in an east-west direction such that the major side slopes are north- and south-facing. Elevation ranges from 256 m at the outlet to 310 m at the highest ridge. The relatively uniform side slopes are periodically interrupted by seven distinct topographic depressions (swales). The catchment is underlain by shale of the Silurian Rose Hill Formation, whereas Shavers Creek watershed includes sandstone, calcareous shale, and limestone. The folded and faulted sedimentary strata were uplifted during the Alleghenian Orogeny ~300 million years ago. Pleistocene permafrost and associated solifluction occurred most recently during and shortly after the last glacial maximum when the area experienced periglacial conditions.

Shallow to moderately deep, gently-dipping to steep, well-drained residual shale soils occur on the ridge tops of Shale Hills, whereas along slopes and in the valley bottom, soils have formed on a colluvial and alluvial mantle of shale chips (Jin et al., 2010; Lin et al., 2006). Soils are typically saturated along the stream where they exhibit redoximorphic features as a result of seasonal soil saturation (Lin et al., 2010). A 3–5 cm organic layer of decaying leaf litter overlies all soils in the watershed. Typical surface soil textures are silt loam, with the percentage of channery shale increasing with depth. Effective rooting depth (depth to bedrock) ranges from 15 cm on ridge tops to 165 cm, especially near valley floor. Soil structure is moderately developed throughout the basin. Small roots have been observed to penetrate into fractured shale beneath the augerable soil.

SSHCZO is characterized by a humid continental climate. Temperatures average 9.5°C, with large seasonal variations: January temperature is –5.4°C, July is 19.0°C. The highest temperature recorded is 33.5°C (April 27, 2009) lowest –24.8°C (January 17, 2009). Annual average relative humidity is 70.2%. Atmospheric deposition in PA is characterized by acidic (pH~4) precipitation. The Shale Hills water balance for 2009–2010 is summarized as follows:

	2009	**2010**
Precipitation (mm)	1028	958
Interception (mm)	284	276
Evapotranspiration (mm)	594	586
Recharge (mm)	319	306
Runoff (mm)	509	364
Runoff ratio (%)	49.51	38.00

The Shale Hills forest ecosystem is dominated by oak, hickory, and pine species. Hemlock, red maple, white oak and white pine line the deep, moist soils of the stream banks, whereas on the drier, shallower north- and south-facing slopes, red oak, chestnut oak, pignut hickory and mockernut hickory are dominant, with Virginia pine appearing on the southern ridge (Naithani et al., 2013). Understory woody species include plants in the Ericaceous family, service berry, hawthorn, raspberry/blackberry, sugar maple saplings, and witch hazel. Forest surveys at the new sites are ongoing.

Historically, the region was logged for charcoal to support a nineteenth and twentieth century iron industry. Today, Shale Hills and the sandstone forest site experience low human impact. Shale Hills is used for recreation and education and the catchment is managed for timber with set-asides for research within the Penn State Forest. The sandstone site is managed by Rothrock State Forest, PA Bureau of Forestry. The lower Shavers Creek watershed is characterized by residential and agricultural land use (row crops and pasture for dairy farms). Research is now being extended into the sandstone catchment, as shown on the map earlier. This new catchment is largely pristine.

The Shale Hills watershed has a comprehensive base of instrumentation for characterization of water, energy, stable isotopes and geochemical conditions. This includes a dense network of sites for soil-moisture observation at multiple depths (120), a network of shallow observation wells (24 wells), soil lysimeters at multiple depths (+80), a cosmic-ray sensor for soil moisture, a research weather station, including eddy flux measurements for latent and sensible heat flux, CO_2, and water vapor, radiation, barometric pressure, temperature, relative humidity, wind speed/direction, snow-depth sensors, leaf-wetness sensors, and a load-cell precipitation gauge. A laser precipitation monitor (LPM: rain, sleet, hail, snow, etc.) was installed in 2008, as were automated water samplers (daily) for precipitation, groundwater, and stream water. Sap flow is measured as a function of tree species. Several hill slope transects have been investigated for collection of soil pore water and gas. Stream, groundwater, and precipitation samples have also been collected and analyzed over extended periods. A wireless sensor network is being deployed to allow near real-time observations of soil moisture, groundwater level, ground temperature, and electrical conductance. Data collected from sensors at Shale Hills are compiled in an online database for use by anyone.

As the new catchments are being implemented, we are decreasing the frequency and spatial density of measurements in the Shale Hills catchment itself. To extend observations to the sandstone and agricultural catchments has required development of a paradigm of fewer measurements per catchment. The new plan targets observations along catenae where soil pits are dug and instruments are deployed.

Three airborne LiDAR flights were flown over the Shavers Creek watershed. The most recent flight (0.5-m resolution) was used to evaluate micro-topography and tree species. Depth to bedrock in Shale Hills has been surveyed. Ground-based LiDAR and total-station surveys were completed for all instrument elevations. Trees >20.3 cm (8 in.) were surveyed for species, biomass, and crown height. Leaf area index (LAI), greenness index, distribution and CO_2 flux have been measured. Borehole logging was completed at three locations to 17 m.

The SSHCZO team is working to quantify the rates of formation and evolution of the structure and function of the Critical Zone, focusing on the fluxes of water, energy, solutes, and sediments (WESS) as a function of the geochemical, hydrological, biological, and geomorphological processes operating in a temperate, forested landscape on sedimentary rock. Our interdisciplinary team works collaboratively in one observatory to advance methods for characterizing regolith and WESS fluxes to provide a theoretical basis for predicting the distribution and character of regolith as well as impacts of regolith on fluid pathways and rates. The modeling effort centers around the Penn State Integrated Hydrological Model (PIHM) (Duffy et al., 2014). Some research highlights are as follows. In hydroclimatology, the instrument array enabled an investigation of explicit coupling and feedback for sub-surface–land surface–atmosphere interaction using fully coupled models (Shi et al., 2013). Biogeochemical measurements of soil N_2 and CO_2, total soil carbon (SC) and dissolved organic carbon are helping to predict how soil development affects SC storage and transport. In ecology, water uptake and isotopic composition of trees are being tracked to understand tree-water use. Stable isotope measurement of deuterium and $\delta^{18}O$ has been used to investigate water fluxes (Jin et al., 2011; Thomas et al., 2013). In geomorphology, rates of regolith formation, the role of tree-throw in the downslope transport of material, and the residence time of material in regolith are being measured (Ma et al., 2010; West et al., 2013). Field-scale and lab-scale tracer tests are being conducted to elucidate preferential pathways and dual-domain solute transport behavior. In hydropedology, ongoing studies target how landscape water influences soil genesis, evolution, variability, and function (Lin et al., 2010). Finally, studies of the physical, biological and hydrogeochemical processes that operate within this catchment though quantification of long-term physical–chemical weathering fluxes are being measured (Brantley et al., 2013).

2.2.2 Expansion to Six Observatories (2009)

2.2.2.1 Christina River Basin Critical Zone Observatory (CRB-CZO)

The Christina River Basin Critical Zone Observatory (CRB-CZO) was established in 2009 as a community platform for research on Critical Zone processes, and is based on a strategic partnership between the University of Delaware (UD), the Stroud Water Research Center (SWRC), the University of Minnesota and numerous other organizations. The 6th order Christina River Basin (1440 km^2) and its four subwatersheds – White Clay Creek (277 km^2), Red Clay Creek (140 km^2), Brandywine Creek (842 km^2), and the tidal Christina River (202 km^2) – flow from Pennsylvania, Delaware, and Maryland into the Delaware Estuary and Bay (Fig. 2.11).

The Christina River Basin transitions from Piedmont into Atlantic Coastal Plain, the two most populated physiographic provinces in the United States.

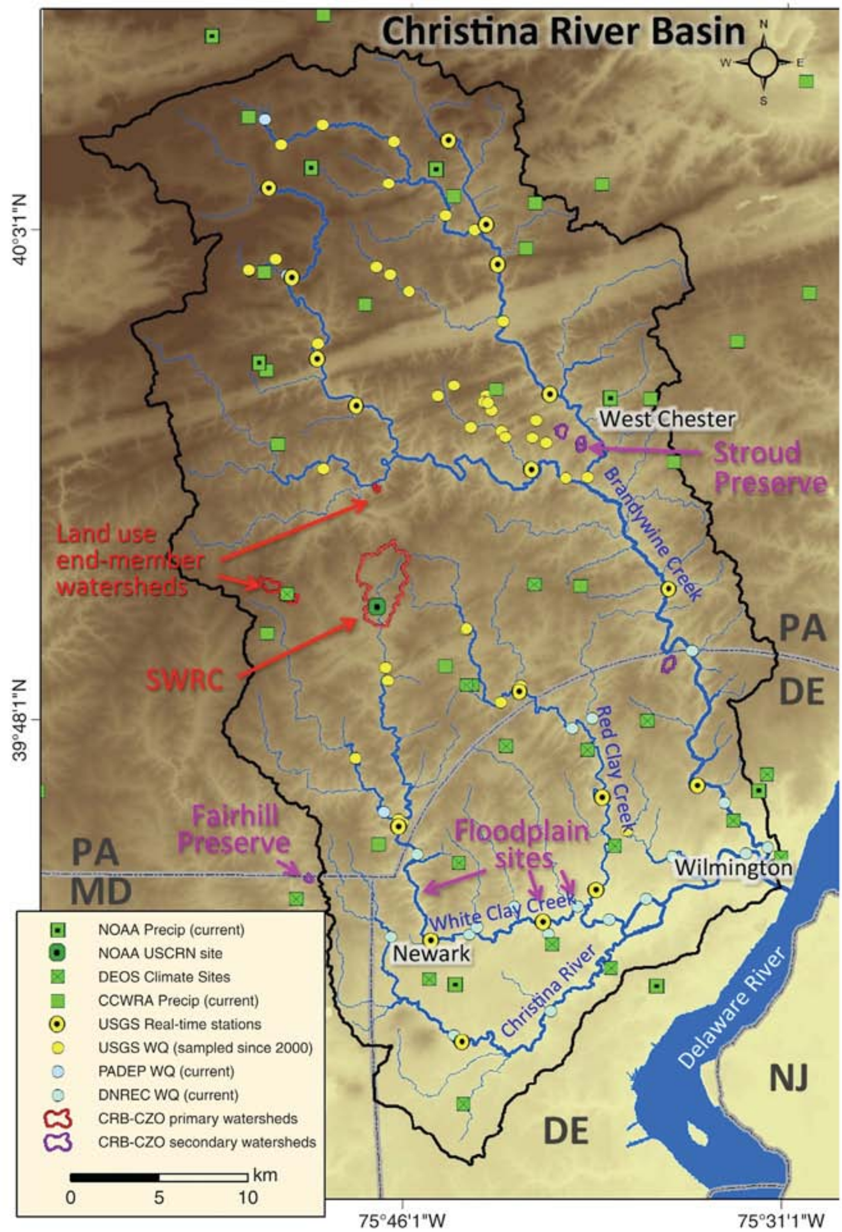

FIGURE 2.11 The Christina River Basin (CRB) is an exceptionally well-studied and well-protected 1400 km^2 watershed that traverses the rural historic colonial corridor between Philadelphia and Baltimore. The CRB thus offers innumerable opportunities to research human impacts to Critical Zone evolution, structure and function through paired and nested plot and watershed approaches.

FIGURE 2.12 Mixed forest and agricultural land uses have dominated the Christina River Basin since colonial times. Although suburban development is very active within the CRB, and urban/industrial land uses are dominant in the lower Christina, most of the core landscapes are preserved by conservation easements and actively protected by a larger number of conservation organizations.

The human footprint within the region spans centuries and current land covers include mature forest, agriculture, suburbia, urban, commercial and industrial (Fig. 2.12), providing an ideal natural laboratory to study the gradient of human impacts on Critical Zone processes. A diverse meta-sedimentary lithology – ranging from micaceous schist and gneiss to quartzite to marble – is overlain by deep, unglaciatied soils of diverse chemical and physical characteristics – from Entisols to Ultisols to Histosols. Nearly all stream valleys are filled with 1–3 m of sediment eroded and deposited since colonial times by intensive deforestation, agriculture and mill damming. White Clay Creek is the only entire watershed designated within the Wild and Scenic Rivers System.

Unique aspects of CRB-CZO include the location in the Piedmont and Atlantic Coastal Plain physiographic provinces, including satellite coastal sites along the Delaware Estuary, the diversity of human land use for centuries, the role as a drinking water source to a million plus people, and its history as being exceptionally well studied by US Geological Survey (USGS), SWRC, environmental protection agency (EPA), and numerous local agencies.

The Christina River Basin and its four sub-basins may be one of the best-studied watersheds of its size in the nation. Studies include seminal fluvial geomorphology of the Brandywine Creek by Luna Leopold, >100 peer-reviewed publications by the Stroud Water Research Center, and extensive long-term monitoring efforts by EPA, USGS and others maintaining quality water supplies to one million people and developing total maximum daily load regulations. Within the CRB exist 19 USGS stream/river gauging stations (6 in DE, 13 in PA) and 5 of the PA stations continuously monitor water quality properties (i.e., turbidity, pH, conductivity, dissolved oxygen). SWRC has historically maintained continuous discharge and other datasets at three stations and is expanding that number for the CZO and other programs. Non-continuous data collected by USGS and SWRC are available for 141 stations. Five USGS stations and a NOAA Climate Reference Network station have continuously recorded weather data.

The holistic study of the entire 1440 km^2 Christina River Basin has the overall goal to integrate the feedbacks among the water cycle, mineral cycle and carbon cycle within contrasting land uses as materials are transported and transformed across geophysical boundaries from "saprolite to sea" that traditionally separate scientific disciplines; that is, bedrock → saprolite → topsoil → aquifers → riparian floodplains → wetlands → river networks → salt marshes → estuaries → sea. Such a study requires a tightly integrated team, sophisticated field sensors and samplers to capture hot spots and hot moments at each geophysical boundary from source to sink, mechanistic models to test the bleeding edge of theory and the coupling of processes with targeted high-resolution data, and a field area that includes both actively weathering and eroding headwaters and actively accumulating depositional zones. Overall hypotheses (Fig. 2.13) are that: (1) Hydrological, chemical, and biological processes that produce and mix mineral surfaces and organic carbon are rate limiting to watershed-scale chemical weathering, soil production and carbon sequestration; and, (2) Humans accelerate rates of carbon-mineral mixing, altering Critical Zone function and resulting in anthropogenic carbon sequestration significant to local, regional and global budgets.

Research highlights from the CRB-CZO include: (1) intensive study sites for the impacts of three land-use end-members (mature forest, row crop agriculture, landfill) on hydrological, pedological, and geomorphological processes; (2) long-term continuous datasets as a basis for hydrological and material transport models, including implementation of the PIHM; (3) intensive geochemical characterization of mineral weathering, carbon-mineral complex formation and carbon stabilization in soils and sediments of different origin and land use; (4) source-to-sink sediment tracing study using radio-isotopes and other geochemical "fingerprints"; and (5) *in-situ* sensors. The CRB-CZO is developing and deploying an advanced sensor network for real-time observations of hydrological and biogeochemical processes. These sensors range from meteorological and hydrological sensors that can be widely deployed at low cost to advanced field instruments such as submersible UV-Vis spectrometry. The wireless

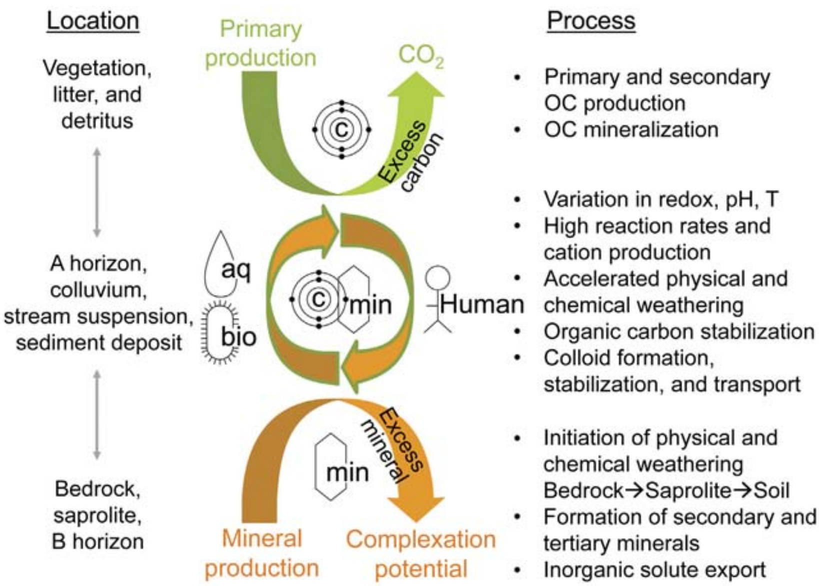

FIGURE 2.13 The conceptual model driving much of CRB-CZO research is that hydrological, chemical, biological, and human processes that produce and mix mineral surfaces and organic carbon are rate limiting to watershed-scale chemical weathering, soil production and carbon sequestration. These processes occur at a range of spatial and temporal scales and across a diversity of landscape positions and environmental settings. Therefore the CRB-CZO maintains that a whole watershed, saprolite-to-sea integration is required to fully understand the feedbacks among these processes.

sensor network is based on the open source electronics "Arduino" platform with ZigBee-based radio networking. With over half a million users worldwide, this approach is robust, easy-to-use and low-cost, which allows SWRC to invest resources on widespread deployment of high quality sensors rather than on data communication infrastructure.

2.2.2.2 Luquillo CZO (LCZO)

The LCZO is located in the Luquillo Mountains of northeastern Puerto Rico in one of the wettest zones of the greater Caribbean Sea region (Fig. 2.14). Over a distance of 10–20 km, the mountains rise from sea level to an elevation of 1075 m while precipitation increases from <1000 mm/year to >5000 mm/year. An overview of the geology, biology, and biogeochemistry of the Luquillo Mountains is found in McDowell et al. (2012).

The two main study watersheds in the watershed, the Río Mameyes and the Río Blanco, have similar climates and environmental histories but differing lithology (Fig. 2.14). The Mameyes watershed (Fig. 2.15) is primarily underlain by volcaniclastic (VC) bedrock that weathers to produce clays and boulders. The Río Blanco watershed is underlain by GD that weathers into a saprolite comprised of sand and large core stones. These differences in weathering patterns

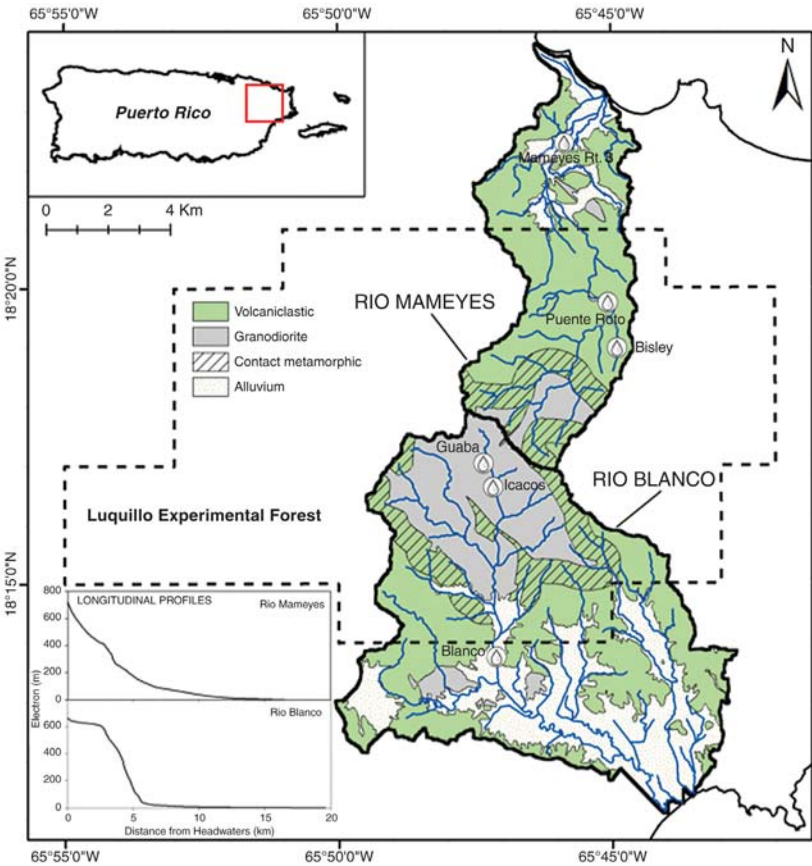

FIGURE 2.14 Location of the LCZO and its primary study watersheds, the Rio Mameyes and Rio Blanco basins. The outline of the Luquillo Experimental Forest is shown as a dashed line. Stream gauges are labeled. Longitudinal profiles of the two basins are modified from Pike et al. (2010).

have a profound influence on landslide frequency, chemical denudation, and the morphology of streams and hill slopes.

The Observatory has a subtropical, humid, maritime climate that is influenced by both orographic and global-scale synoptic weather systems. Rainfall occurs throughout the year and exceeds 5000 mm/year at the highest elevations. Rainfall events at mid-elevations are generally small (median daily rainfall 3 mm/day) but numerous (267 rain days per year) and of relatively low intensity (<5 mm/h). Nevertheless, individual storms greater than 125 mm/day occur annually, and daily rainfalls greater than 600 mm have been recorded (McDowell et al., 2012).

Six Holdridge life zones occur in the Luquillo Mountains and surrounding areas: lower montane wet, lower montane rain, subtropical moist, wet, rain, and dry (Ewel and Whitmore, 1973). Luquillo forests are classified into four main types: "tabonuco forest," so named for the dominant tree *Dacryodes excelsa*,

FIGURE 2.15 Rio Mameyes at the La Mina waterfall. Waterfalls are important geomorphic breaks in the river systems of the Luquillo Mountains, which structure the aquatic biota above and below the break (Covich et al., 2009). *(W. McDowell.)*

which covers lower elevations up to about 600 m and harbors about 168 tree species. The "Colorado forest," named for *Cyrilla racemiflora* trees, occurs above the tabonuco forest and extends to about 900 m. This forest type is a montane cloud forest that has a canopy of about 15 m and harbors 53 tree species. At this same elevation, and in especially steep and wet areas, is the third forest type, the "palm forest," which is dominated by *Prestoea acuminata*. On the highest peaks are the "elfin forest," a dense, short-statured cloud forest with abundant epiphytes and a canopy that can be less than 3-m tall.

Two striking features of the region's disturbance regime are the long history of natural hurricanes and the recent history of human disturbance and recovery. In addition to hurricanes, other natural disturbances include landslides, tree falls, floods, and droughts. Human disturbances are most common at lower elevations and include historic clearing for pasture, crops, and coffee plantations; logging; road construction, and water diversions.

Researchers have access to 11 stream gages, 2 walk-up canopy towers, 4 meteorological stations, 3 deep observation wells, 20 shallow riparian wells, lysimeter nests, an extensive GIS system and numerous long-term vegetation plots at the site. Because the Luquillo Mountains have been a center for research on tropical forests for over a century, many long-term environmental data sets exist. Three signature data sets include (1) micrometeorology and hydrology: hourly and daily measurement of radiation, air pressure, temperature, relative humidity, precipitation, wind speed, and wind direction (four stations maintained by USFS-IITF). The world's longest known record of weekly rainfall and through fall, and associated chemistry is maintained at the site and available online. Eight stream gages are maintained by the USGS, and the USFS-IITF maintains three stream gages in the Bisley Watershed. (2) Geochemistry and biogeochemistry: the LCZO is developing an extensive data set of Luquillo soils and bedrock geochemistry. The chemistry of weekly rainfall, through fall, and stream flow is maintained and available from the LCZO and Luquillo LTER web pages. Additional data are available on plant species composition, allometry, and chemistry. (3) Spatial data sets: a 10-m DEM and associated spatial data sets are also available for the upper Luquillo Mountains.

The role of hot spots and hot moments in tropical landscape evolution and Critical Zone function is the overarching focus of the LCZO. The infrastructure, sampling strategy, and data management system are designed to address this question in watersheds underlain by GD and VC bedrock in the natural laboratory of the Luquillo Mountains, Puerto Rico. LCZO research is centered on four interrelated focal areas: (1) the importance of knick points and different landscape positions as hot spots for weathering, soil development, and biogeochemical cycling; (2) the role of hot spots and hot moments in redox cycling, and their effects on weathering, as well as the storage and loss of carbon and nutrients in soils over a range of spatial and temporal scales; (3) the role of hot moments in the transport of sediment, C, and nutrients in stream flow, and hot spots that determine the distribution of material across the landscape; (4) scaling up hot spots and hot moments in time and space using climate and hydrologic modeling, and assessing the role of rain, cloud water, and dust inputs on landscape evolution and Critical Zone function. Overall, the research conducted by LCZO will provide a well-integrated assessment of Critical Zone properties and processes that scale from microsites to catenae, watersheds, landscapes, and the region; and from minutes to hours, days, months, and years. Because of the long-term ecological studies that are also conducted at the site, the LCZO is ideally suited to examine interactions between Critical Zone processes and the biology of tropical forests.

2.2.2.3 Santa Catalina Mountains – Jemez River Basin CZO

The Santa Catalina Mountains – Jemez River Basin Critical Zone Observatory (SCM-JRB CZO) was established in 2009 as part of the National CZO Program funded by NSF. It comprises an elevation gradient that begins with a granite-schist "sky island" mountain range rising out of Sonoran desert scrub

FIGURE 2.16 The Santa Catalina Mountains – Jemez River Basin CZO comprises two geographical locations (in Southern Arizona and Northern New Mexico) to capture a climatic parameter space that encompasses much of the water-limited Southwestern United States.

in southern Arizona (SCM) and extends into a rhyolite montane caldera in northern New Mexico (JRB) (Figs 2.16 and 2.17). Inclusion of both sites in the observatory design enables researchers to explore a wider range of CZ-forcing parameter space than would be possible with either site alone. The CZO includes lithological, climatic, and disturbance variation characteristic of much of the southwestern United States (Chorover et al., 2011).

Precambrian- and Paleogene-aged granites and GD, in combination with Paleozoic-aged metamorphic rocks such as schist and quartzite, dominate SCM bedrock. The terrain is steep and rugged. Soils are shallow at low elevation (<25–50 cm depending on landscape position) where weathering depth is limited by hot, dry climate conditions, and deeper (ca. 50–100 cm) at higher elevation where cool, wet conditions prevail. Schist soils are more deeply weathered, finer in texture, and contain more organic matter than granite soils (Lybrand et al., 2011; Pelletier et al., 2013).

Silica-rich extrusive volcanic rocks dominate JRB bedrock: rhyolite tuff, rhyolite, andesite, dacite, and silica-rich volcanic ash. Instrumented catchments in JRB are located primarily on rhyolite tuff, which facilitates formation of deep soils (70–>200 cm depending on landscape position). The thick soil cover corresponds with a relatively diffuse landscape structure. Tuff-derived soils exhibit substantial clay accumulation in the subsurface. Upper soil horizons contain appreciable volcanic glass and kaolin, whereas subsurface horizons have less glass and more smectite (Vazquez-Ortega et al., 2014).

Instrumented zero order basins (ZOBs) are in Upper Sonoran Desert, Desert Woodland-Grassland, Ponderosa Pine, and Mixed Conifer forest ecosystems that have been managed for multiple use. Both SCM and JRB have been subjected to regular wildfires, including two in 2011 and 2013 in the Valles Caldera

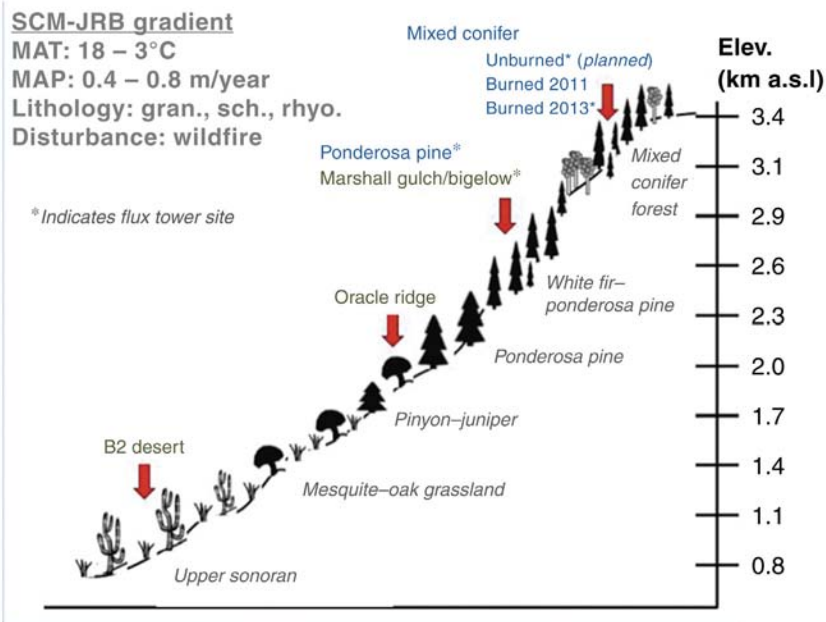

FIGURE 2.17 Ecosystems colonizing the SCM-JRB CZO extend from Sonoran Desert scrub to mixed conifer forest. Mean annual temperature decreases and mean annual precipitation increases with increasing vegetation from 800 m to 3400 m above sea level. Forests at higher elevations are seasonally-snow covered.

National Preserve (VCNP, JRB) that provide a chronosequence of mixed conifer forest disturbance. Pre- and postfire, LiDAR studies combined with sediment flux, topographic incision analysis and ^{10}Be cosmogenic radionuclide data indicate that ca. 99% of long-term denudation occurs during the brief pulses of erosion that immediately follow wildfire (Orem and Pelletier, 2015).

Precipitation and temperature throughout the southwestern United States are highly dependent on elevation, and SCM-JRB climate covers much of that encountered in the southwestern United States. Most of the water-sustained urban populations in semi-arid basins of the southwestern United States. (e.g., Tucson, Phoenix, Albuquerque, El Paso) originates in snowpack delivered to montane sites (Harpold et al., 2012). As a result, the dynamics of snowpack accumulation and ablation, including the impacts of wildfire disturbance, are of significant societal concern (Harpold et al., 2014a, 2014b). The SCM-JRB CZO seeks to better resolve the water, carbon, and weathering dynamics of high elevation receiving catchments, including their resilience to climatic variation and associated disturbances such as wildfire.

ZOBs nested within catchments are an integrating unit of study in the SCM-JRB CZO (Chorover et al., 2011; Perdrial et al., 2012). For example, as shown in Fig. 2.18, two instrumented ZOBs are situated within the Marshall Gulch

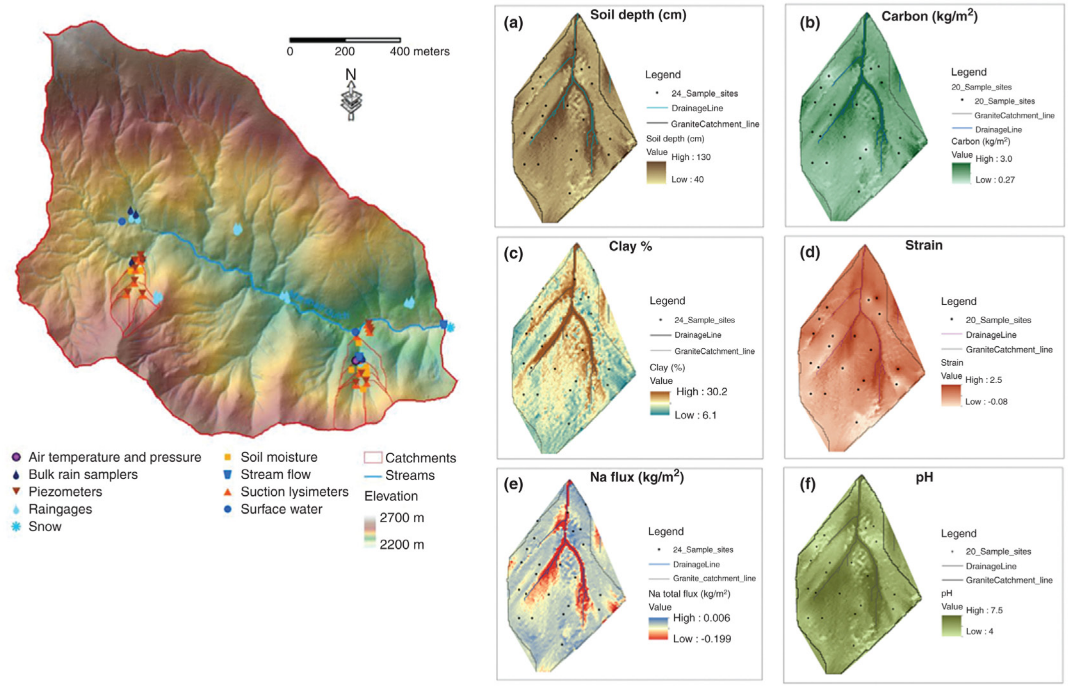

FIGURE 2.18 The SCM-JRB CZO has instrumented zero order basins (ZOBs) nested within catchments. For example, the Marshall Gulch Catchment (1.54 km^2, in the SCM, left side of figure above), located southeast of Mount Lemmon peak (32°25'45"N, 110°46'0"W)) contains a weir for integrated response and instrumented ZOBs such as the "granite ZOB" shown above right (Holleran et al., 2014).

Catchment in the SCM: the western ZOB is underlain by granite whereas the eastern ZOB is underlain by schist. The mean transit time of water in this catchment shows strong dependence on initial conditions (Heidbuchel et al., 2012). Digital maps of soil properties in the granite ZOB of Marshall Gulch are shown in (a) to (e) at right (Holleran et al., 2014).

At each location (JRB and SCM), field equipment deployed in ZOBs provide continuous or periodic measures of water, carbon, and energy stores and fluxes across the CZ. Instrumentation includes flux towers for measuring eddy covariance, sap-flow sensors, phenocams, weather stations, rain gauges, rainwater samplers, stream flow flumes, snow-depth sensors, snow-melt lysimeters, shallow groundwater piezometers, soil–moisture and soil–temperature probes, soil–water tensiometers, and soil–water solution samplers.

The SCM-JRB CZO focus is on understanding how variability in climate, lithology, and disturbance influence CZ structure and function over both short (e.g., hydrologic event) and long (e.g., landscape evolution) time scales. We are addressing this issue using a theoretical framework that quantifies system inputs in terms of effective energy and mass transfer (EEMT, MJ/m year, Rasmussen et al., 2011, see Fig. 2.19). Science questions being addressed in the current phase of CZO research include: (1) How do long-term drivers of CZ structure and function (EEMT and tectonics) interact with parent material to control current CZ structure and response to perturbation? (2) How is long-term CZ evolution affected by ecosystem process controls? (3) What is the impact of CZ structure on buffering climate- and disturbance-driven variability in water, soil, and vegetation resources, and how does this translate into changes in CZ services? Highlights of SCM-JRB research so far include the recognition that isotope hydrology, trace element geochemistry, pedogenic studies, and landscape evolution modeling show that weathering trajectories at the pedon and

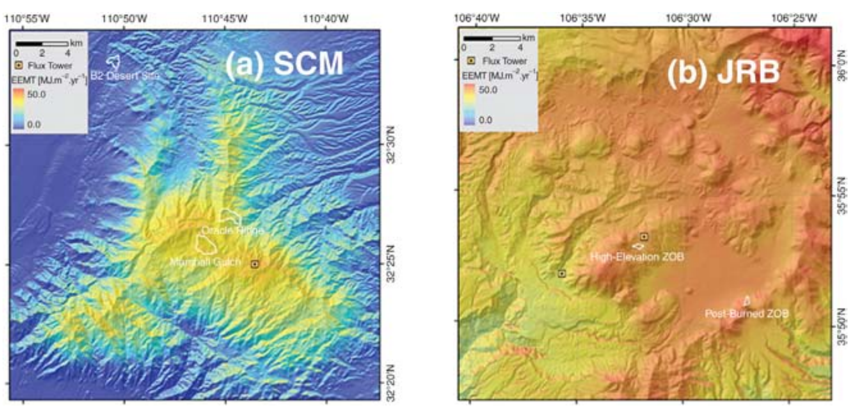

FIGURE 2.19 EEMT maps of the SCM (a) and JRB (b) surfaces and associated instrumented sites enable visualization of how climatic forcing varies with elevation (as manifest in water and carbon throughputs to the CZ subsurface).

ZOB scale exhibit strong dependence on landscape position and lithology in similar water/energy (EEMT) regimes. In addition, CZ evolution occurs episodically; landscape-disturbance events, such as wildfire, disproportionately affect long-term rates.

2.2.3 Creating a CZO Network and a National Office (2014)

2.2.3.1 Calhoun CZO

The Calhoun CZO is located in north central South Carolina, in the Southern Piedmont physiographic province that extends from Virginia to Alabama (Fig. 2.20). The new Calhoun CZO leverages more than 60 years of USDA Forest Service and Duke University research on land and water degradation and soil change based at the Forest Service's Calhoun Experimental Forest in the Sumter National Forest (Richter et al., 2014; Fig. 2.21). Calhoun investigators include researchers and educators from Duke University, University of Georgia, Georgia Tech, University of Kansas, Mississippi State University, Roanoke College, as well as the USDA Forest Service.

The Calhoun CZO aims to improve understanding of the dynamics and evolution of biota, landforms, soils, saprolites, hill slope hydrology, stream channels, and sediments that comprise the CZ with belowground systems that are ancient (>10^6 years), deep (~30 m on interfluves), and of advanced-weathering stage, commonly with no weatherable primary minerals for many meters below

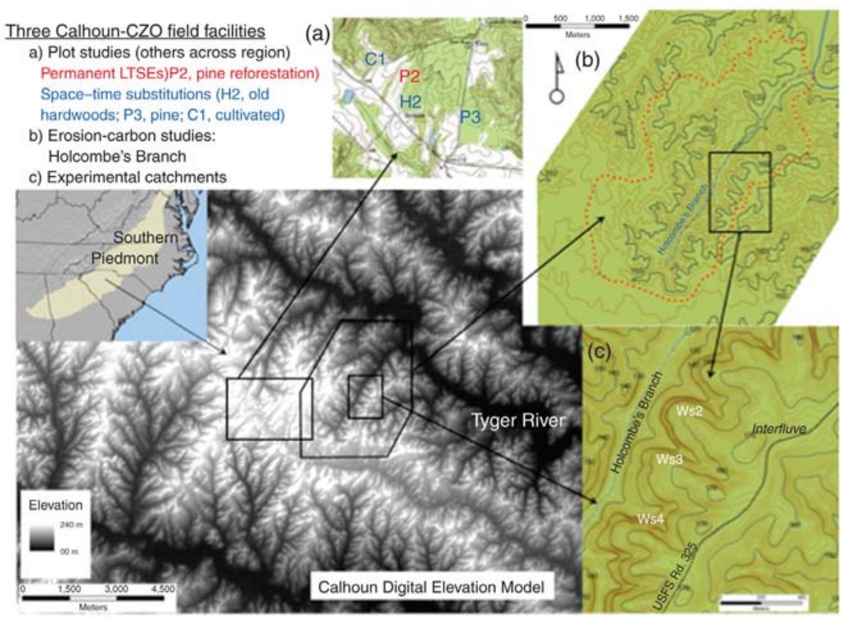

FIGURE 2.20 Three Calhoun CZO field facilities located on topographic and DEM maps.

FIGURE 2.21 A circa 1948 photograph of the USDA Forest Service's Calhoun Experimental Forest showing the intensity of soil erosion and land degradation that had occurred at this site prior to reforestation to the present state.

the ground surface (Markewitz et al., 1998; Bacon et al., 2012). These attributes suggest a portion of the CZ that is highly vulnerable to human alteration, and indeed, much of the Southern Piedmont including the Calhoun Experimental Forest has a history that involves some of the most serious agricultural land and water degradation in the nation. By the mid-twentieth century, nearly 18 cm of soil over more than 10 million ha were estimated to have been lost to erosion, rivers carried enormous sediment yields, cultivation-based crops were no longer viable, and large numbers of farmers had abandoned the land.

By the late twentieth century, the eroded and commonly abandoned Piedmont farmland had been extensively reforested (Fig. 2.22), motivating many to adopt the perspective that the degraded land had been restored in a matter of decades by a process known as "old-field succession." The Calhoun CZO research team has a more critical perspective, and is guided by a hypothesis that the impressive reforestation masks fundamental alterations in CZ hydrology, geomorphology, biology, and biogeochemistry and that post-disturbance CZ evolution may not so much recover as restabilize in altered states. Given all this, the Calhoun CZO provides an important opportunity for meeting the growing need to understand CZs "in the face of land use change … to inform strategies for sustaining a wide range of human activities" (from NSF's CZO Program Solicitation, NSF 12-575).

The Calhoun CZO team seeks to understand how Earth's CZ responds to severe soil erosion and land degradation. Re-instrumented catchments are used to measure and model changes in ecohydrology and biogeochemistry of

FIGURE 2.22 A circa 2006 photograph from the Calhoun Experimental Forest showing the current reforested state of the Piedmont region.

interfluves, hill slopes, and terraces that were historically subject to accelerated erosion and deposition. Calhoun research focuses on how land use stresses networks and processes that connect the CZ's surface and subsurface subsystems. Calhoun researchers use historic and contemporary data of vegetation, soil, catchments, and sensor networks to help hind cast and forecast CZ dynamics and evolution across temporal and spatial scales.

A key objective of the Calhoun CZO is to help integrate contemporary and historic land use into CZ science since over most of Earth's surface CZs are affected by natural and human forcings. Calhoun CZ science aims to be transformational in exploring the CZ's lower boundary conditions and processes, and the CZ's evolution following land degradation. The Calhoun CZO is organized by research questions motivated by the concept that the CZ is an integrated system from the atmosphere and upper plant-canopy boundary layer to the water in the deepest aquifers and that human forcings typically accelerate CZ processes associated with vegetation, atmosphere, and surface hydrology and soils, thus stressing temporal and spatial networks that connect surface and deep subsurface components of the CZ.

The questions that organize Calhoun CZO research build directly on past research at the site and span multiple scales of time and space: (1) Do land-use change, land degradation, and erosion decouple upper and lower CZ systems by destroying macro porosity networks that are conduits of gas and water

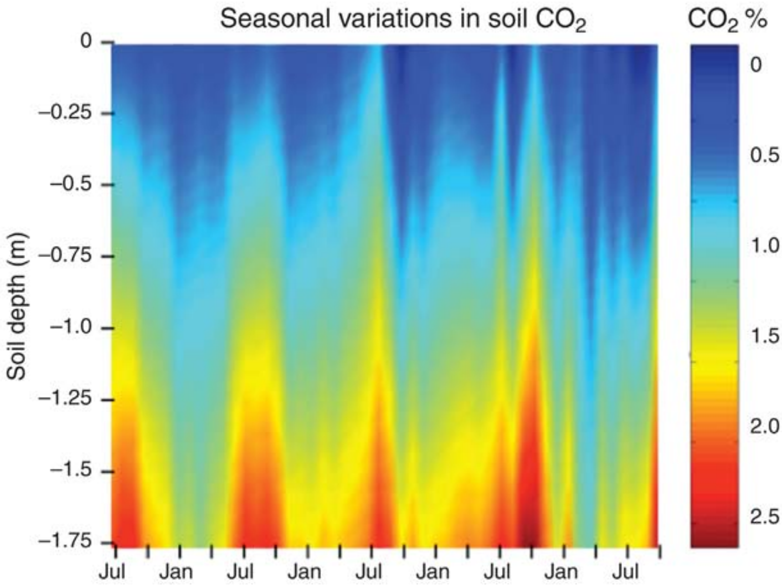

FIGURE 2.23 Deep CO_2, soil solid, and solution data will be greatly expanded in Calhoun CZO studies (Oh et al., 2004; Richter and Markewitz, 2001).

exchange? How rapidly can re-forestation recover CZ porosity and re-network the CZ into an integrated system? (2) How has the legacy of severe erosion redistributed and altered organic carbon dynamics on both eroded uplands and in anoxic alluvium filled with historic sediment (Billings et al., 2010)? (3) How do human-forced changes in the CZ interact with human livelihoods, adaptation, and governance? (4) Can human-forced CZs enter new steady states, complete with positive feedbacks and attractors that resist recovery?

Re- and up-instrumented catchments, first instrumented by hydrologists in the late 1940s, will allow investigators to measure, experiment, and model ecohydrologic and biogeochemical dynamics from interfluves to a variety of hill slopes to toe slopes and terraces, all across multiple temporal and spatial scales (Fig. 2.23). Sensors connected by wireless networks and samplers of gases and water will be co-located along transects and in depth-dependent arrangements to examine the recovery of integration in the degraded Critical Zone systems. Interdisciplinary models are being coupled with radiocarbon and stable isotope analyses to hind cast and forecast system hydrology, soil properties and processes, and overall CZ biogeochemistry.

The Calhoun CZO is a center for research and education. The CZO is linked to a Duke University IGERT – training center on intelligent sensor networks; annual CZO science meetings will have oral and poster presentations, discussions, and training sessions that involve scientists and students as fundamental members of the CZO team. We plan a range of outreach efforts to local, regional, and national publics with multi-media science, history, and community-based components, using field days, hardcover books, op-eds, Facebook, and Twitter. An important focus of the CZO is on undergraduate research and education, and we are developing a set of classroom-tested, web-based laboratory, and classroom activities for undergraduates and advanced high school students based, in part, on real-time and historic data from the Calhoun CZO.

2.2.3.2 Eel River

The Eel and Russian rivers are the two large river systems of coastal Northern California (Fig. 2.24), with the Eel draining northward through mostly timber and grazing lands (but with increasing irrigated agricultural use), and the Russian draining to the south through increasing vineyard and housing development towards Santa Rosa, the largest city in the basin. Although more developed than the Eel, only about 13% of the Russian watershed is in agricultural lands. The Eel has two dams in the main stem headwaters where the Potter Valley diversion reroutes Eel flow into the Russian River. The Russia River has two large dams, one in the headwaters (that receives flow from the Eel), and one on a major tributary, Dry Creek, farther down the river. But like other river systems in active agricultural lands, the Russian has some 500 small dams along the tributaries. Salmon (including the endangered Coho Salmon) spawn and migrate in both the Eel and Russian; their populations are in great decline, which is attributed to many factors, including reduced summer base flows and elevated temperatures (Katz et al., 2012).

The Eel and Russian have competed over geologic time for drainage area at their mutual headwaters as tectonic pulses swept through the region (Lock et al., 2006). The underlying geology of this region records the complex accreted terrain of the North American plate margin. Three dominant rock types exist in the Franciscan terrain of northern coastal California: the Coastal Belt (argillite, sandstones and conglomerates), the Central Belt (mélange) and the Eastern Belt (metasedimentary and metavolcanic rocks) (Fig. 2.24), with the Central Belt swept by large, active earthflows in the mechanically weak rocks (e.g., Mackey et al., 2011; Mackey and Roering, 2011; Booth et al., 2013). Most of the Eel River watershed emerged above sea level in just the past 4 million years (Lock et al., 2006) and uplift rates increase from south to north from about 0.4 mm/year to greater than 4 mm/year (Merritts and Bull, 1989). Despite high uplift and erosion rates (Fuller et al., 2009; Willenbring et al., 2013), a deep and well-developed, hydrologically active weathered bedrock zone has formed on Coastal Belt rocks (Salve et al., 2012) (no studies have been done yet on the Central and Eastern Belts).

A striking pattern in the Eel watershed is the correspondence between the three geologic units and the dominant vegetation (Fig. 2.24). The Coastal and Eastern Belts support conifer forests, whereas hardwood trees and herbaceous vegetation predominate in the mélange of the Central Belt. The vegetation distribution does not follow elevation or precipitation patterns. We hypothesize that the approximate correspondence of vegetation type with bedrock results from higher available moisture at higher water potential (less negative pressure) in

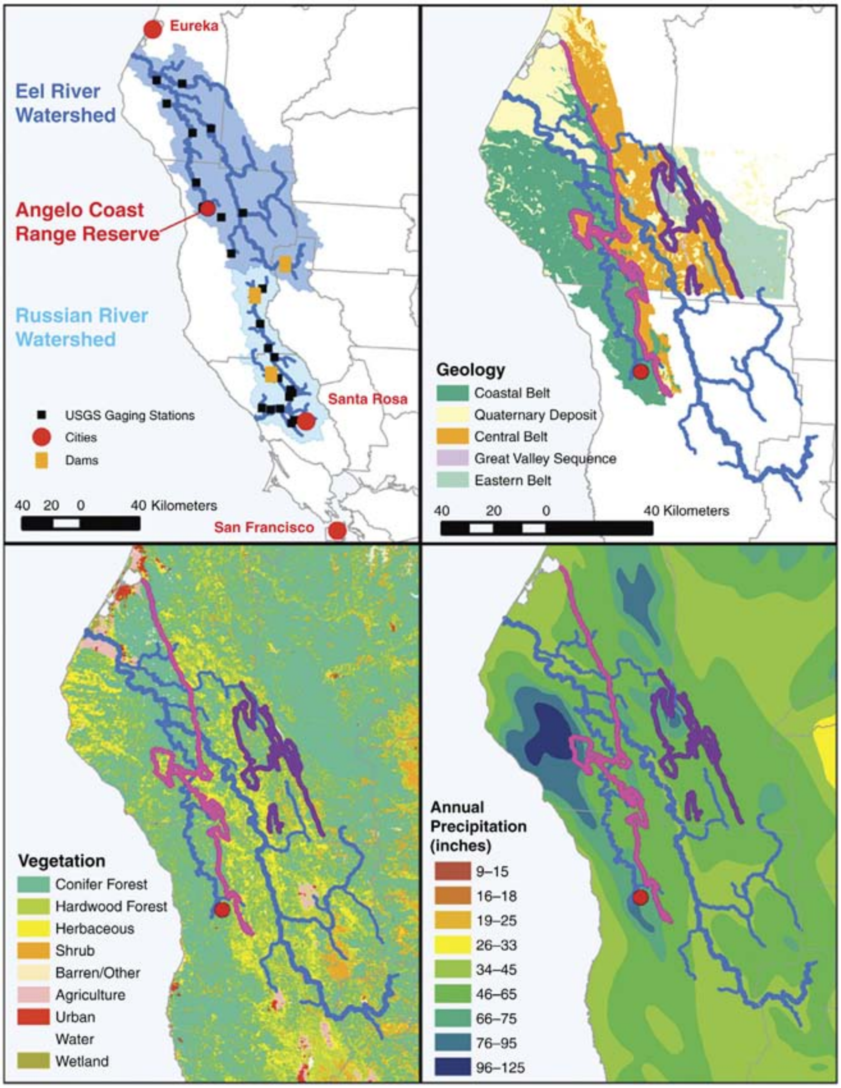

FIGURE 2.24 Watershed and Angelo Coast Range Reserve locations and patterns of mean annual precipitation, dominant vegetation, and geology in Northern California. Pink line is the western boundary between the Coastal and Central Belt bedrock in all maps. Purple line denotes eastern boundary of Central Belt with Eastern belt. Note their approximate correspondence with conifer and hardwood to hardwood/herbaceous boundary. *(Precipitation data and the vegetation map are from the Cal-Atlas geospatial clearinghouse (precipitation mean from 1900 to 1960). Geology map is from the California Geological Survey (data are lacking to the east and south).*

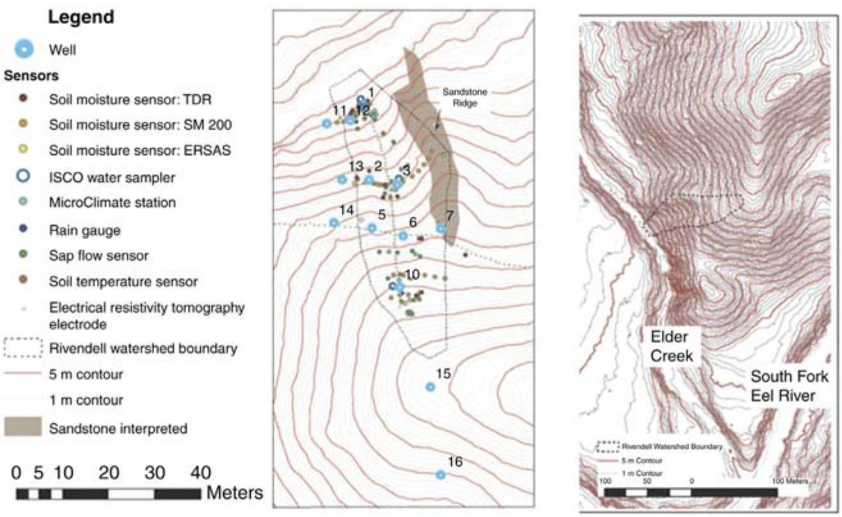

FIGURE 2.25 Location of Rivendell site on Elder Creek (right panel) and instrumentation field at the site (left panel). The instruments include time-domain, reflectometry probes (TDR), and Electrical Resistance Sensory Array System (ERSAS) (Salve, 2011) for relative rock moisture profiles. Contour interval is 1 m in both cases. *(Modified from Salve et al. (2012).)*

the fractured bedrock of the Coastal and Eastern belts than in the fine-grained mélange. Rainfall in this region is strongly seasonal, with summer months hot and dry, hence, deep sources of moisture may be critical for plants.

The Eel River observatory is based mainly in the Eel River watershed (Fig. 2.24), and is composed of four nested components, increasing in spatial scale from an intensively instrumented hill slope to a region encompassing both the Eel and Russian River watersheds (Figs 2.24 and 2.25):

1. Rivendell, a 4000 m^2 sub-basin of Elder Creek located in the Angelo Coast Range Reserve, where hill slope-scale intensive field investigations have been underway since 2007 (Fig. 2.25).
2. The Angelo Coast Range Reserve, a University of California Berkeley-administered research reserve in the University of California Natural Reserve System, protecting 31 km^2 of steep forested terrain, 5 km of the upper South Fork Eel River and the entire watersheds of Elder Creek and several other tributaries.
3. The entire Eel River watershed (9546 km^2).
4. Rivers of the California North Coast, focusing on Eel and Russian River systems (13,800 km^2).

2.2.3.2.1 Rivendell

In 2007, researchers at the University of California at Berkeley (UC Berkeley) began an intensive monitoring program of the Critical Zone on a small (~4000 m^2) steep sub-basin, nicknamed “Rivendell,” on a north-facing hill slope adjacent to

Elder Creek (Salve et al., 2012). Elder Creek is a tributary of the South Fork Eel River in Northern California within the Angelo Coast Range Reserve (Fig. 2.25).

The ~30° hill slope at the Rivendell installation site is underlain primarily mudstone (argillite). Cosmogenic dating of sediments (Fuller et al., 2009), direct measurement of bedrock erosion (Stock et al., 2005), and modeling (Seidl and Dietrich, 1992; Sklar and Dietrich, 2006) have documented active channel incision driving hill slope processes, with a local pace of about 0.2–0.4 mm/year. A wireless radio network, powered by treetop solar panels, supports a dense sensor network for environmental monitoring. A network of 12 wells as deep as 30 m have been drilled through weathered bedrock and into fresh bedrock. The installation includes extensive soil and rock moisture monitoring devices, sap-flow sensors on 30 trees, and 4 meteorological stations (Fig. 2.25). The entire system, some 750 sensors, together with a USGS stream gauge, record data at <30-min frequency. These data are transmitted every 4 h to UC Berkeley and placed into a sensor database that displays them near real-time. Four automated ISCO samplers are used to collect water samples (daily or more frequently during runoff events) for water chemistry analysis. Repeated campaigns are carried out to sample water for isotope analysis. Weather stations are also located in the meadow across from Rivendell, at two other nearby meadows, and at Cahto Peak (at the headwaters of Elder Creek).

Figures 2.26 and 2.27 illustrate the Critical Zone profile and hydrologic processes. The Rivendell site crosses a hill slope that faces north where it borders Elder

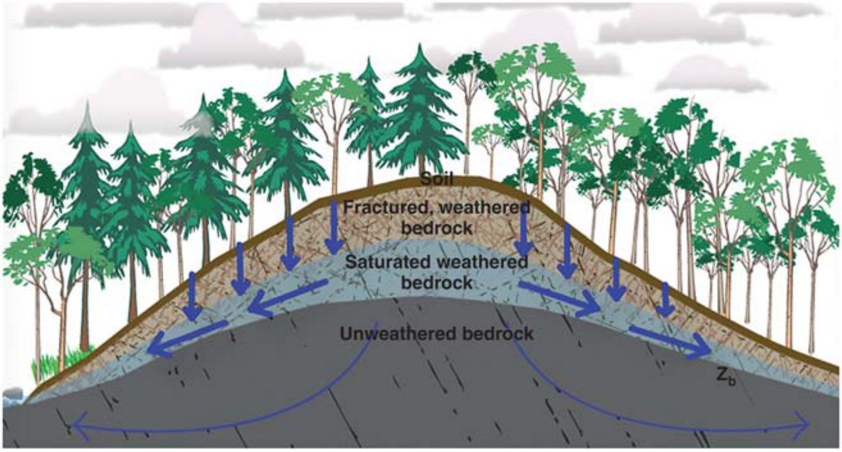

FIGURE 2.26 An idealized cross-section through the Rivendell study site. The conifer Douglas fir-dominated hill slope (left side) faces North whereas the evergreen leaf trees (e.g., Madrone, *A. menziesii*; Tan Oak, *Notholithocarpus densiflorus*; California bay, *U. californica*) dominate the south-facing slope. Soils on the underling argillite are thin (<50 cm), stony and highly conductive. No overland flow occurs. Instead excess precipitation passes through the fractured, weathered bedrock (vertical arrows) and perches on the boundary between the weathered and fresh bedrock (Z_b). This perched water forms a seasonally dynamic groundwater that runs laterally to channels (sloping arrows), providing both storm flow and, importantly, the summer base flow that sustains the river ecosystem. Rempe and Dietrich (2014) presented a simple model for the elevation profile of Z_b under hill slopes. *(Figure modified from Rempe and Dietrich (2014).)*

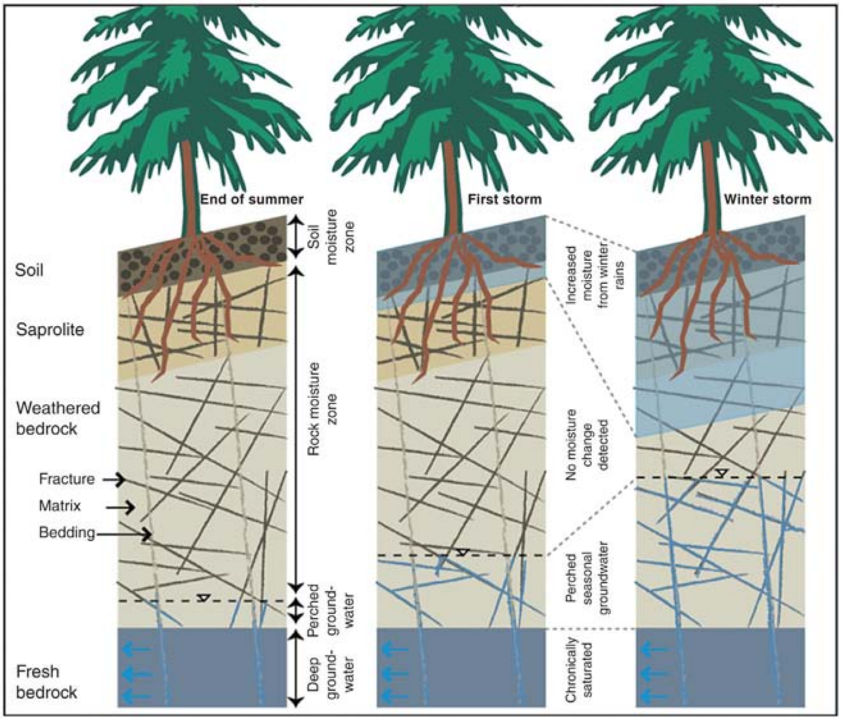

FIGURE 2.27 Illustration of how winter rains vertical structure and seasonal rapid injection of winter rain via fracture flow to a perched water table as soil and saprolite and weathered bedrock more slowly gain moisture (from Salve et al., 2012).

Creek and the ERCZO will extend monitoring to the south-facing slope where it borders what may be an ancient deep-seated landside. Douglas fir (*Pseudotsuga menziesii*), up to 60-m tall mixed with evergreen hardwoods such as interior live oak (*Quercus wislizeni*), madrone (*Arbutus menziesii*), and California bay (*Umbellularia californica*) dominate the north-facing slope, whereas madrone mixed with oak and bay dominate the south-facing slope. Shallow stony soils overlie vertically dipping argillite with interbeds of lenticular sandstone bodies, the largest of which defines and outcrops along the eastern divide of the north slope. The argillite intensely fractures upon weathering forming a soil-like material (saprolite) near the surface and fracture density decreases with depth. This weathered bedrock layer is bounded by fresh bedrock (Z_b) (Fig. 2.26).

All excess precipitation travels vertically through the weathered bedrock, perches on the dense fresh bedrock and then flows to adjacent streams. Figure 2.27 illustrates a proposed seasonal cycle of rain and subsurface moisture change and runoff. First rains at end of summer (September and October) advance moisture into the soil and a limited distance into the weathered bedrock. Some of that rain water flows along fractures, reaching the groundwater causing minor water table rise. Subsequent rain in the winter advances a wetting front through the weathered bedrock zone and delivers water to a dynamic, fractured-controlled groundwater response system (Salve et al., 2012). Graduate student led research has been initiated on: (1) prediction of the Critical Zone development (Rempe and Dietrich, 2014); (2) dynamics of runoff and rock moisture availability to the forest canopy (Oshun et al., 2012); (3) chemical evolution of water and gasses through the Critical Zone (Kim et al., 2012, 2014); and (4) influence of vegetation on regional climate (Link et al., 2014).

2.2.3.2.2 Angelo Coast Range Reserve

The Angelo Reserve is one of forty natural reserves protected by the University of California Natural Reserve System for university-level teaching and research. Angelo is the field base for the Eel River Critical Zone Observatory and where meetings and workshops will be held. From 2004 to 2013, researchers and students from 50 different institutions, including 19 California colleges and universities, and 28 outside of California, with an average of 1571 user-days per year, used Angelo. Mapping, monitoring, and experimental field manipulations within the reserve over the past 25 years have documented the food-web ecology during summer low flow and biogeochemical dynamics along the upper South Fork Eel River and twelve of its tributaries, including Elder Creek (Power et al., 2008, 2009; Finlay et al., 2002, 2011; Kupferberg et al., 2011; Sabo and Power, 2002a,b; Suttle et al., 2004, 2007; Wootton et al., 1996). Among many findings, this work has identified a drainage area or network-based dependency in many ecosystem attributes, including total-dissolved nitrogen, algae abundance and taxonomic distribution, salmonid densities and energy sources, and aquatic insect emergence. Current research is revealing remarkable patterns of aquatic insect migration and reproduction that link main stem and tributary food webs in ways that support summer-rearing salmonids (Uno and Power, 2013). Other ongoing research probes environmental temperature, nutrient and flow thresholds that differentiate salmon-supporting ecosystems from those degraded by cyanobacteria blooms.

The Eel's summer base flow is entirely derived from slow drainage of perched ground water in the Critical Zone, which also influences stream temperature and nutrient loading. Continuous thermal records (15-min frequency) from iButton recorders deployed throughout the study basin are available for several years. Seven water level recorders in tributaries, established to investigate sediment transport (Scheingross et al., 2013) also show strong diurnal oscillations in water level, a signal that can be seen down the South Fork Eel to drainage areas of 642 km^2. Interestingly, tributaries of similar location and size differ in magnitude and timing of fluctuations. These data offer an opportunity to establish more directly the link between terrestrial vegetation and stream flow and temperature.

The Environmental Center lies at the south boundary of the Angelo Reserve, which is still on the electrical grid. This complex of buildings includes a large (30–50 person) meeting room supported by a small kitchen, two laboratories and a microscope room supporting chemical, biological, and earth science research, a screened lathe house for experimental work under ambient light and temperatures, a computer room, and a small office. Wireless Internet connections are available throughout the complex.

2.2.3.2.3 Eel River Watershed

By scaling up to the entire Eel River watershed (9546 km^2) researchers at the ERCZO are exploring how different rainfall, topography, vegetation, and geology regimes affect Critical Zone currencies and their ecosystem consequences. Collaborations among climate scientists, ecologists, and ocean scientists have documented and predicted the influence of algae and nutrients flushed from the Eel River into coastal marine ecosystems (Olhsson, 2013; Ng, 2012). The plume from the Eel appears to be associated at times with increased coastal primary production (as visible from satellite records). Salmon and lamprey migrations also connect the ocean to the river. The Eel River watershed is of sufficient size to apply climate modeling. Seasonal water balance changes are detectable in GRACE imagery. The Eel River has 10 USGS real-time stream gauges, which tap drainages of different mean precipitation, vegetation, and geology. The ERCZO maintains an additional former USGS stream gauge ("Branscomb") within the Angelo Reserve on the South Fork Eel.

2.2.3.2.4 California North Coast region, focusing on Eel and Russian Rivers

Twenty-one stream gauges are operated by the USGS on the Russian River, along with another 17 operated by the State Water Resources Control Board (SWRCB) and National Marine Fisheries Service (NMFS). This high level of monitoring reflects the importance of water in the Russian River, especially for agricultural and domestic use and as critical flow for the survival of salmonids. Great concern occurs about significant drawdown during water spraying in the spring (to protect vineyards from frost) and its effects on survival of the juveniles of the endangered and threatened salmon species (Deitch et al., 2008; NMFS, 2009). Rising stream temperature, perhaps due to reduced summer flows, is also a concern. Extreme low flows due to drought or water withdrawals that warm main stems above temperatures tolerable to salmonids, favor invasive warm-water fishes including pike minnow that threaten salmonids (Reese and Harvey, 2002), and in the Eel River, have been associated with localized toxic cyanobacteria blooms (Puschner et al., 2008).

Research Focus: Through intensive field monitoring in the Critical Zone, researchers at the ERCZO are following watershed currencies – water, solutes, gases, sediment, biota, energy, and momentum – through a subsurface physical environment and microbial ecosystem into the terrestrial ecosystem, up into the atmosphere, and out through diverse drainage channel networks in which aquatic ecosystems interact with these currencies, mediating the delivery of nutrients to coastal ecosystems at the river mouth. Nine Berkeley faculties from four departments and three different colleges lead the ERCZO research.

In the first five years of the ERCZO, the primary research questions are: (1) Does lithology control rock moisture availability to plants and therefore overall resilience of vegetation to climate change in seasonally dry environments? (2) How are solute and gas effluents from hill slopes influenced by biota in changing moisture regimes? (3) What controls the spatial extent of wetted channels in the channel networks of seasonally dry environments? (4) Will changes in Critical Zone currencies induced by climate or land use change lead to threshold-type switches in river and coastal ecosystems?

Synthesis modeling will incorporate ERCZO advances in understanding mechanisms at a finer scale, couple the different Critical Zone subsystems, and be used to explore long-term and large-scale consequences of the dynamics of the Critical Zone in the context of climate and land-use change, and water management policy.

2.2.3.3 Intensively Managed Landscapes CZO

The intensively managed landscapes (IML) CZO (Fig. 2.28) consists of two core sites: the 3,690 km^2 Upper Sangamon River Basin in Illinois and 270 km^2 Clear

FIGURE 2.28 Locations of the study sites in the Intensively Managed Landscapes CZO.

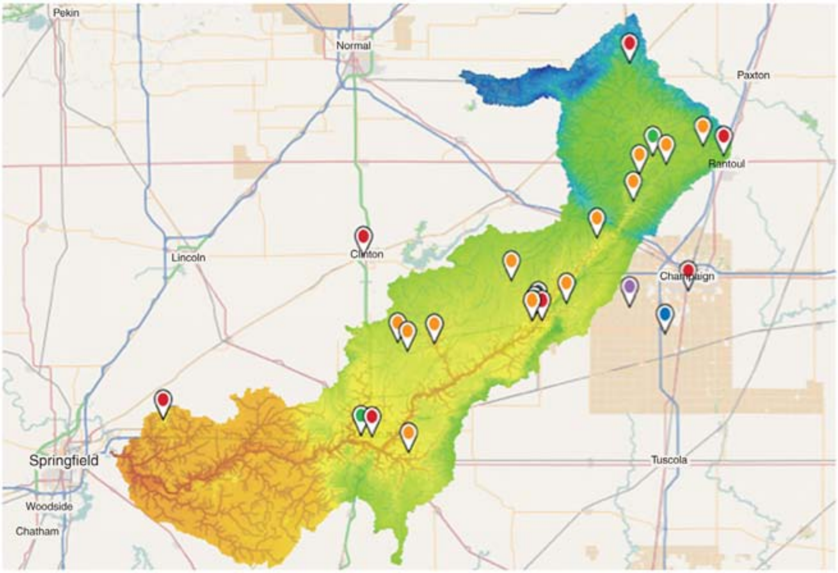

FIGURE 2.29 Monitoring locations of select variables in the Upper Sangamon River Basin, IL. The teardrop colors represent different variables or groups of variables monitored at this site.

Creek Watershed in Iowa, along with the 44,000 km^2 Minnesota River Basin in Minnesota as third participating site. These sites together represent a broad range of physiographic variations occurring throughout the glaciated Midwest.

The Upper Sangamon River Basin (USRB; Fig. 2.29) is a well-studied watershed, representative of low relief, glaciated regions in the Midwest (Keefer et al., 2010). The USRB is intensively managed (USDA, 2006), following conversion to agricultural production from native, tall grass prairie in the 1800s (Gates, 1934; Bogue, 1951). Subsequently, tile installation in poorly drained soils; construction of drainage ditch systems, and channelization of headwater reaches drained seasonal wetlands and altered the hydrology and biogeochemistry of the region (Alexander and Darmody, 1991; Fig. 2.30).

The Clear Creek, IA Watershed (CCW; Fig. 2.31) empties into the Iowa River in east-central Iowa. Clear Creek is representative of most Midwestern watersheds with its mollic soils, humid-continental climate with freeze-thaw cycles, and predominantly agricultural land use (Bettis, 1995; Abaci and Papanicolaou, 2009). The combination of intensive agriculture with a wet climate on highly erodible soils has dramatically decreased the time for material transport through the system, making Clear Creek a good example of the shift from transformer to transporter (Papanicolaou and Abaci, 2008; Wilson et al., 2009; Dermisis et al., 2010; Wilson et al., 2012).

The Minnesota River Basin (MRB) feeds to the Upper Mississippi River Basin and the main stem of the river is actively aggrading with many of its

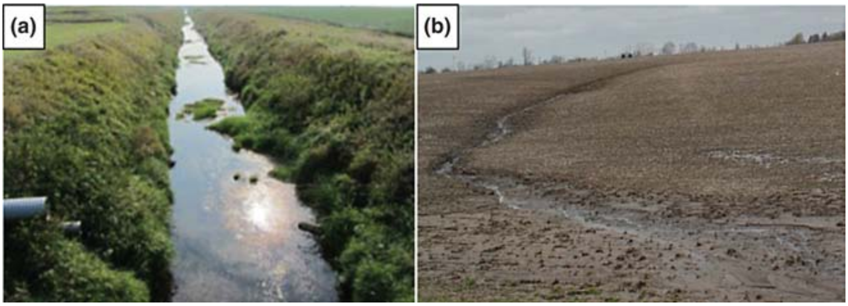

FIGURE 2.30 Anthropogenic activities in the IML CZO include: (a) channelization and tiling, as well as (b) tillage, that have altered Critical Zone processes and services.

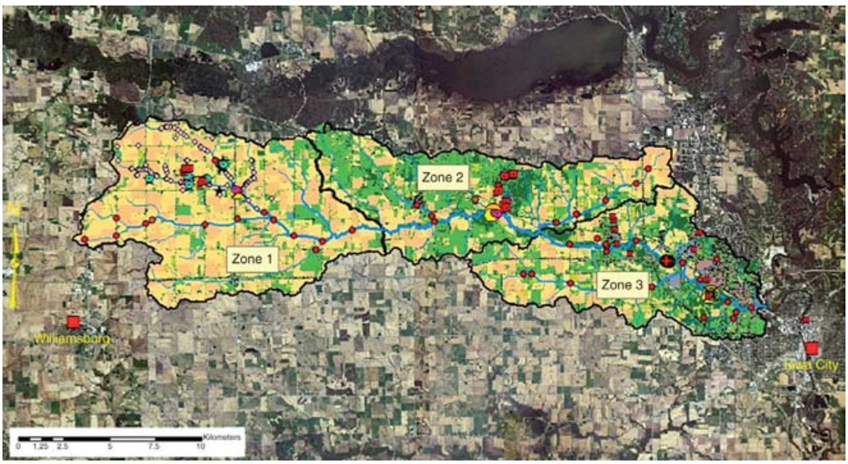

FIGURE 2.31 The established measurement locations in the Clear Creek, IA watershed.

tributaries rapidly incising (Wilcock, 2009; Gran et al., 2009). Following retreat of the Wisconsin ice sheet, glacial Lake Agassiz catastrophically drained through the proto-Minnesota River valley resulting in a nearly instantaneous, 70-m vertical incision of the main stem (Thorleifson, 1996; Belmont et al., 2011), which produced steep gradient knick points at the confluence of each tributary along the main stem.

The IML-CZO combines the breadth and depth of expertise in research and education pertaining to the sustainability of Critical Zone processes and services from eight academic institutions, namely the Universities of Illinois, Tennessee, Iowa, Northwestern, Pennsylvania State, Purdue, Minnesota, and Utah State. Additionally, the partnerships exist with researchers and scientists from several state and federal agencies in the Midwest including the Illinois State Water Survey, Illinois State Geological Survey, Iowa Geological Survey, and United States Geological Survey.

Agricultural intensification, artificial drainage, wetland loss, and urbanization in IMLs of the US Midwest have dramatically altered the Critical Zone extending from the top of the plant canopy to the depth of mineral weathering (e.g., Amundson et al., 2003) in the soil column. Less than one percent of the Midwest's original tall grass prairie has been left unmodified and although this extreme transformation (Fig. 2.1) has made the region a global agricultural leader, it has also had many other far-reaching, often deleterious effects on the Critical Zone (e.g., Mutel, 2008; Papanicolaou et al., 2011). To assess better the short- and long-term resilience of the key Critical Zone services in IMLs related to biodiversity, ecology, hydrology, geomorphology, and climate, an observational network has been established consisting of three sites in Illinois, Iowa, and Minnesota. These sites capture the geological diversity of the low relief, glaciated, and tile-drained landscape in the Midwest. This IML-CZO aims to understand better the present day dynamics of managed landscapes in the context of their long-term co-evolution with soils and biota. Ultimately, the IML-CZO will provide informed management strategies to reduce the vulnerability of the IMLs to present and emerging trends in human activities such as bioenergy crop expansion (Le et al., 2011) and climate change (Kumar, 2013), as well as help develop the next generation of scientists and practitioners to sustain the Critical Zone processes and services.

The central hypothesis of the IML-CZO is that the Critical Zone of IMLs has passed a tipping point (or threshold) and has gradually shifted from being a transformer of material flux with high nutrient, water, and sediment storage to being a transporter of material flux with low nutrient, water and sediment storage. Much of this shift can be attributed to human modification of the landscape. Anthropogenic management of the landscape has reduced storage and residence times, and the emergent patterns of connectivity, dynamics, and responses reflect this change in the residence times. Further, this shift in landscape conditions may affect the capacity of the Critical Zone to acclimate to future impacts, that is, its resilience, associated with ongoing human activity or with extreme weather events caused by climate change. As a result, this trajectory of rapid land-use change is unsustainable for maintaining and enhancing critical services. Conservation programs have helped reverse this course in some instances, but a comprehensive scientific underpinning of these strategies will be further guided by IML-CZO (e.g., Nikolaidis, 2011; Banwart, 2011; Papanicolaou et al., 2011; Banwart et al., 2012).

Through strategic measurements, analysis, and modeling, the IML-CZO is addressing the following questions centered on the hypothesis given earlier: (1) How do different time scales of geologic evolution and anthropogenic influence interact to determine the trajectory of critical structure and function? (2) How is the co-evolution of biota, consisting of both vegetation and microbes, and soil affected due to intensive management? (3) How have dynamic patterns of connectivity, which link across transition zones and heterogeneity, changed by anthropogenic impacts? (4) How do these changes affect residence times and aggregate fluxes of water, carbon, nutrients, and sediment?

Two overarching objectives have been developed from these questions through five key research thematic areas. The first objective is to evaluate changes in the Critical Zone of the Midwest by examining the following:

- Glacial legacy effects of surficial geologic materials as they influence the Critical Zone response to human impacts by establishing baseline conditions of soil resilience, as well as landscape and soil evolution trajectories and rates.
- The interplay between intensive cultivation, with increased commodity and bioenergy crop production, and changing weather patterns (i.e., prevalent freeze–thaw cycles, intense rain events, and droughts), as it alters soil organic matter storage and export with implications to soil aggregate structure evolution, landscape water holding capacity, microbial activity, runoff partitioning to surface and subsurface flow, soil strength, and erodibility.
- Anthropogenic alteration of the hydrological landscape with engineered drainage infrastructure through tiles, as it affects water fluxes and biogeochemical cycling in surface and subsurface domains through changes in residence times and biogeochemical transformations and transport.
- Channelization through drainage ditches and headwater extensions as it alters regimes of hydrologic transport, sediment production and storage, and changes drastically landscape morphodynamic processes.

The second objective is to capture the connectivity of modern hydrological, geomorphological, and biogeochemical processes along different flow paths by quantifying the stores and residence times of water, soil/sediment, SOM/nutrients, identifying provenance across scales, and assessing shifts in the system behavior through measures of thresholds, resilience, reversibility/irreversibility to change, and hysteresis using key state variables for all phases under forcings of climate and local anthropogenic activity.

Along with *in situ* and remote sensing measurements, analysis and modeling will be used to: (1) quantify the fluxes and transformations, interactions, thresholds, and dynamic feedbacks of water, nutrients, and sediment; and (2) assess how rapid land use changes have altered the vulnerability and resilience of these systems. These studies will range from event dynamics to longer time scales that are shaped by long-term dynamics. The CZO will take advantage of existing and new infrastructure to measure short-term dynamic fluxes of water, soil aggregates, crop residue, and soil organic matter during high-intensity rains in early summer (Elhakeem and Papanicolaou, 2009), and also during freeze-thaw cycles. Common or core measurements and associated protocols will be consistent with that of the other CZOs. Additionally, the IML-CZO will make specific measurements that are unique to the characteristic of the study sites.

Characterization of post-settlement alluvium (PSA), unique to IML-CZO, will provide the historical movement of sediment at the hill slope and subwatershed scales to determine time-incremented, sediment-delivery ratios. PSA will be investigated using GPR and coring coupled with fly ash and radiogenic nuclide (i.e., ^{137}Cs and ^{210}Pb) studies. Through experiments, IML-CZO will measure fluxes of water, sediment, and carbon, as well as enrichment ratios (i.e., measure of SOM enrichment in eroded soil relative to that in the soil column), the role of aggregates in stabilizing SOM, and decomposition. It will also measure net ecosystem exchange (NEE), water-vapor flux, radiation and heat energies, using eddy flux towers to understand the impact of climate change on vegetation (Drewry et al., 2010a,b) and subsequent impact of the Critical Zone processes. To quantify dynamic surface and groundwater interactions, tracking of water, solute/particle, and C, N, P between the landscape and stream channels will be conducted. Additionally, the impact of tile drainage networks on transport and transformation will be characterized through measurements of tile-drainage intensity, drainage coefficient, and the flashiness index, as well as the hysteresis in water, sediment, and nutrients. Finally, dynamic measurements will include storm-based evaluations of sediment production and transfer with field measurements of lag times, enrichment ratios, and sediment concentrations. Event-based sediment rating curves will be developed to determine the hysteresis in the system and will be complemented with sediment source fingerprinting.

2.2.3.4 Reynolds Creek

The Reynolds Creek (RC) CZO was established in 2013 and is located in the Reynolds Creek Experimental Watershed (RCEW) in southwestern Idaho. The RC CZO is based on a strategic partnership among the United State Department of Agriculture – Agricultural Research Service (USDA-ARS), Northwest Watershed Research Center (NWRC), Idaho State University and Boise State University. The RCEW has been administered by the USDA-ARS-NWRC for over 50 years. The RCEW is an ideal location for the establishment of a SC CZO for the following reasons: (1) the RCEW is an intermediate scale watershed (239 km^2), (2) it is physically diverse and has a wide range of climate conditions, (3) it supports a preexisting, long-term, spatially extensive data collection, and (4) it is the site of evaluation of land-management practice. These features are further expanded on in the following sections.

The RCEW encompasses a wide range of ecohydrological environments typical of the intermountain region of the western USA. An extensive description of the RCEW environment can be found in Seyfried et al. (2001a). The environmental variability is driven by the nearly 1000-m elevation range and variable geology. Precipitation in the RCEW is not strictly a function of elevation, but generally increases with elevation from less than 250 mm/year to greater than 1100 mm/year while mean annual temperature decreases about 5°C. Rain is the dominant form of precipitation in the RCEW, with snow dominating in the highest elevations. Corresponding vegetation types include sagebrush steppe in the lower elevations, transitioning to mountain sagebrush, western juniper, aspen, and coniferous forest (Fig. 2.32).

The existing scientific infrastructure is a key advantage for the RCEW site as a CZO. Most CZO sites require substantial funding to produce a

FIGURE 2.32 Vegetation types include sagebrush steppe in the lower elevations and transition to mountain sagebrush, western juniper, aspen, and coniferous forest.

hydro-meteorological network that falls short of that available currently at the RCEW. This network is critical because it forms the basis for understanding how the soil environment varies over time and space. Detailed descriptions of the RCEW and published data can be found in Hanson (2001); Hanson et al. (2001); Marks (2001); Seyfried et al. (2001a, 2001b, 2001c, 2001d, 2011); Slaughter et al. (2001); Nayak et al. (2010); Chauvin et al. (2011); Reba et al. (2011a, b) (see also ftp.nwrc.ars.gov for data).

The existing, publically available hydroclimatic data are long-term and spatially extensive. The long-term nature of the data research can be conducted in the context of the climate at different locations and how it is changing. An increase in temperature (1–2°C), reduction of snow, and temporal shift of stream flow with no change in total precipitation or soil-water storage has been documented at the RCEW (Nayak et al., 2010; Seyfried et al., 2011). The spatially extensive nature of the data is critical, given the now understood horizontal, as well as vertical, variability of the climate within the RCEW. These data are not collected on a regular grid, but spaced with higher density in areas of steeper environmental gradients and at specific special study sites.

Characterization of the soil environment, as opposed to the climate, is central to this CZO. The original network of soil-water and temperature-data collection, which extends back more than 30 years, has been dramatically expanded in the last 10 years to include robust, well-calibrated (Seyfried et al., 2005) soil

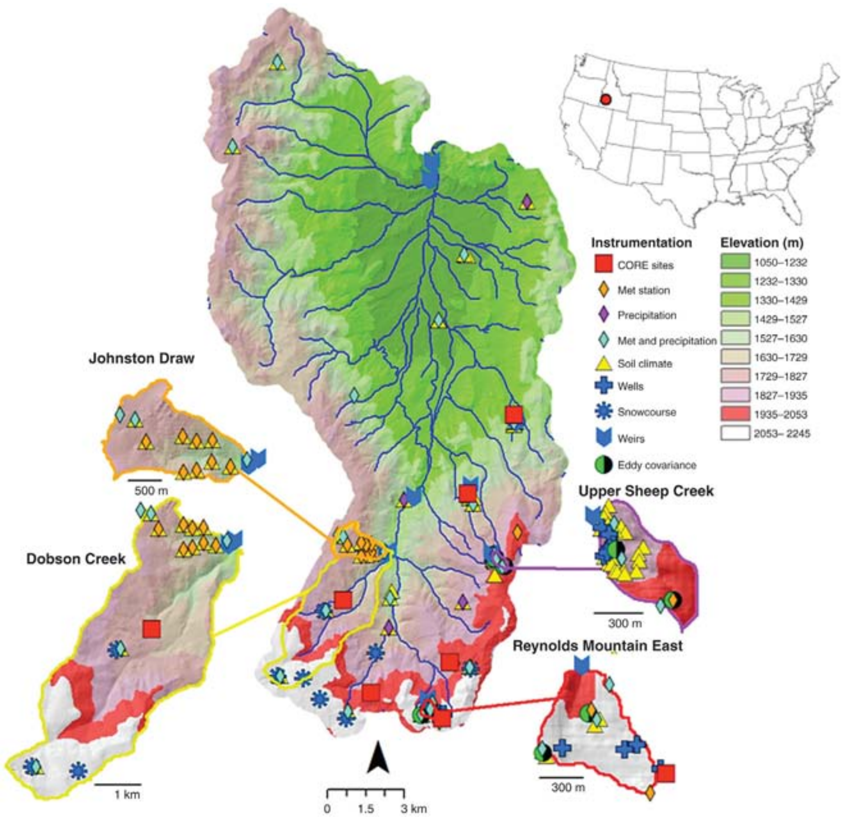

FIGURE 2.33 The RC CZO extends from ~1000 m in elevation to over 2200 m and a wide range of vegetation and climate. Instrumentation including CORE sites for eddy covariance (EC), current meteorological, precipitation, soil-climate stations, wells, snow courses and weirs are shown with different symbols.

water and temperature sensors. These kinds of data are necessary for confirming the accuracy of the SC models used to calculate SC dynamics across the landscape (e.g., RCEW). Note that data collection is spread throughout the RCEW and also concentrated in specific research sites. For example, data collected at Johnston Draw is intended to elucidate topographic influences (Fig. 2.33), while that at Upper Sheep Creek is focused on differential snow distribution. Other sites (not shown) are oriented toward grazing effects in the low elevations.

SC varies widely within the RCEW, both in amount and type. For example, at one, high-elevation site under aspen and affected by snow drifting, the depth-weighted average (150 cm) soil organic carbon (SOC) content is 20.3 g C/kg with no measureable SIC. (Soil pH is about 6.3 at all depths.) This is contrasted with a depth-weighted average SOC content of 5.0 g C/kg at a low elevation, much-drier site under sagebrush. At the low-elevation site, however, 39.8 g C/kg of SIC was measured, so that considerably more total SC is stored at the low-elevation site. Strong vertical gradients of SOC occur in both profiles, and no SIC was detected above 76 cm at the low-elevation site. This "flipping" of the predominant SC form with elevation, or more precisely, with soil environment, is evident in the detailed, watershed-specific soil survey that was conducted at the watershed (Stephenson, 1977).

Determination of present day C balance, in conjunction with the water balance is critical. The existing five EC instruments have been used for hydrological research to date (Marks et al., 2008; Reba et al., 2009, 2012; Flerchinger et al., 2010, 2012) but C flux has been monitored throughout, providing a potentially powerful starting point. The instruments will be redeployed to reflect a shift in research emphasis to include C fluxes at drier, SIC dominated sites.

Reynolds Creek has LiDAR (point clouds and processed bare earth rasters) for the entire experimental watershed, with a point-cloud density of ~5 pts/m^2. The dataset is adequate for estimation of aboveground biomass estimates for large shrubs and trees but is not entirely sufficient to resolve estimates of aboveground, sagebrush-steppe biomass estimates. Fire frequency and extent are increasing in the Western United States with changes in climate (Westerling et al., 2006) and vegetation (introduced species such as *Bromus tectorum* (cheatgrass)) (Allen et al., 2011). Use of prescribed fire as a management practice has emerged as a tool to control fuel loads (McIver et al., 2010); the NWRC has undertaken a prescribed fire management program in cooperation with the Bureau of Land Management (BLM). The NWRC selects sites, conducts experiments and monitors and evaluates fire effects, whereas the BLM assists in site selection and conducts the fires. The primary ecohydrological criteria for site selection is that precipitation be sufficient such that invasive species such as cheatgrass, and yellow star thistle do not expand as a result of the fire. To date, three fires (2002, 2004, and 2007) have been conducted in the RCEW. The next fire is scheduled for 2015. The temporal sequence of past fires and the ability to participate in the planning of future fires provides a rare opportunity for research into the effects of fire on SC.

In general, the management and ownership of the RCEW lands are typical of much of the western United States, which is to say that the RCEW is a "working" as opposed to a pristine, watershed. Most of the land in the watershed (77%) is owned by either the state or federal government, and, in this case, managed by the BLM. The remaining, privately held land is managed by local ranchers, primarily four families that live in, or adjacent to the watershed and derive their livelihood from cattle ranching. In addition to cattle grazing, a small part of the valley is used to raise hay and some timber harvesting occurs. The mission of the NWRC compliments the objectives of the CZO program: "To provide knowledge and technology for management of semi-arid rangeland watersheds; to quantitatively describe the hydrologic processes and interactive influences of climate, soils, vegetation, topography, and management on rangeland systems; to develop information, simulation models, and tools that can be used by action agencies and producers in determining optimum management strategies; and to maintain long-term databases for scientific applications." Much of the success of the unit has been through cooperative research with academic institutions. In fact, the RCEW is intended to provide a springboard for complimentary research. Accommodation, with Wi-Fi and rudimentary lab space is provided for visitors, which typically log about 100 visitor-hours each year.

RC CZO is focused on the quantification of SC (C) and the Critical Zone processes governing it. Most of the world's terrestrial C is found in the Critical Zone (Lal, 2004), where it is predominantly stored as SC and sensitive to climate change and land management. Despite its importance, SC remains a large source of uncertainty in both C cycling and global climate models (Jones et al., 2005; Friedlingstein et al., 2006; Cadule et al., 2010; Falloon et al., 2011; Hopkins et al., 2012). That uncertainty arises due to both an incomplete understanding of the processes dictating SC fate and the challenge of up-scaling commonly highly spatially and temporally heterogeneous soil processes to the landscape or global level (Todd-Brown et al., 2013).

Conceptual models of SOC dynamics are being revisited as flaws in traditional models are identified (Conant et al., 2011; Schmidt et al., 2011; Hopkins et al., 2012). Indeed, consensus is growing that rates of SC storage and release are not particularly sensitive to the chemical properties of the organic C (Marschner et al., 2008; Amelung et al., 2008; Kleber and Johnson, 2010; Conant et al., 2011; Schmidt et al., 2011). Instead, soil physical, chemical, and biological variables (e.g., soil moisture, temperature, structure, bacterial assemblage, root behavior, bio char), more strongly dictate SC fate (Torn et al., 1997; Jobbágy and Jackson, 2000; Davidson and Janssens, 2006; Sollins et al., 2007; Ekschmitt et al., 2008; Totsche et al., 2010; Conant et al., 2011).

Understanding and predicting SC and associated processes are further complicated by the fact that most studies are conducted at the plot scale, but processes operating at larger spatial and temporal scales such as fire and vegetation change may ultimately determine the impact of SC on the global budget (Westerling et al., 2006; Trumbore and Czimczik, 2008). For example, increasing burn frequency or area, a trend in much of the Western United States (Westerling et al., 2006), may return C to the atmosphere faster than it can accumulate, as observed in fire-prone Mediterranean and boreal regions (Harden et al., 2000; Trumbore and Czimczik, 2008). Moreover, a scaling challenge exists in distributing SC, a Critical Zone property that is highly heterogeneous in nature, across the landscape. To address this challenge, many environmental parameters have been used to describe SC distribution using statistical approaches (Arrouays et al., 1998; Jobbágy and Jackson, 2000; Kulmatiski et al., 2004; Garcia-Pausas et al., 2007; Hirmas et al., 2010; Kunkel et al., 2011), yet these approaches are limited because they often use surrogates for the soil environment (precipitation, topography, etc.) rather than actual soil environment variables (soil water content, temperature, or net water flux), and they are not necessarily transferable and grounded in process-based understanding.

The RC CZO is addressing the grand challenges of improving prediction of SC storage and flux from the pedon to landscape scale. The overarching hypothesis is that soil environmental variables (e.g., soil water content, soil temperature, net water flux) measured and modeled at the pedon and watershed scale will improve our understanding and prediction of SC storage, flux, and processes. Research priorities for the CZO include: (1) determining the relationship between measured SC storage and the soil environment at high spatial resolution across a broad, regionally significant environmental gradient; (2) measuring net C flux in conjunction with components of the SC cycle (soil respiration, litter decomposition, SC characteristics) at the pedon to landscape scale; (3) evaluating SC model performance in terms of: (a) SC distribution across the landscape, and (b) representation of critical C fluxes at the pedon to landscape scale; (4) being a community resource and magnet for global climate modeling and C cycle research.

2.2.3.5 CZO National Office

The growth in size and scope of the CZO program led to the recognition that a National Office (NO) was a primary need, and one was formalized in 2014. The goals of the CZONO include enhancing communication among CZO researchers and students, promoting common measurement and data protocols, providing a single point of contact for the CZO program for the public and other scientists, developing new educational and outreach initiatives for students at the graduate, undergraduate and K-12 levels, and enhancing interaction of the CZO program with a broad range of scientists, all within a framework of advancing Critical Zone science as a tool for sustainability. The NO will accomplish these goals by: establishing regular communication among CZO PIs, organizing two national meetings annually, offering graduate/young scientist's workshops, and developing electronic delivery of educational resources for Critical Zone science. The CZONO will lead the maintenance and further development of the criticalzone.org website, a key resource for the CZO and the broader scientific community. It will develop and maintain a visible presence in the scientific community at national and international meetings and via new media. The office will also seek to identify and raise funds for larger initiatives, including international summer schools in Critical Zone science and a national Critical Zone K-12 education strategy. An important function of the CZONO will be to integrate scientists and students currently outside the CZO community to take advantage of the CZO as an outstanding scientific resource. The office will act as a liaison between the CZO program and related US programs including CUAHSI, NEON, and LTER. It will act as a liaison to international programs such as SoilTrEC, the EU CZO program, and the French RBC (Network of River Basins), and other evolving CZO and CZ-related networks for example in China, Australia, and other European nations. Improved integration with other science programs that have overlapping goals will extend the Critical Zone network concept over a wider range of environments and processes than the US CZO program can achieve on its own.

2.3 COMMON SCIENCE QUESTIONS

The 10 US CZOs represent a wide range of geological, climatic, and land use settings that can provide an opportunity to develop a broad and general understanding of the evolution and function of the Critical Zone. By identifying shared or "common" research questions across these CZOs, an opportunity arises to advance new understanding in key issues. The work of many CZOs can accomplish what no one observatory can provide. This is due to the diversity of sites, as well as the diversity of the researchers who collectively bring the essential observational and theoretical skills and knowledge to these common problems.

Research at the CZOs involves the following shared conceptual framework: (1) The Critical Zone evolves a structure that influences the storage and flux of water, solutes, sediments, gases, biota and energy. (2) By mediating these stores and fluxes, the Critical Zone provides ecosystem services, and is thus critical to people.

As well, CZO research may be summarized by the following three general shared questions: (1) What controls Critical Zone properties and processes? (2) What will be the response of the Critical Zone structure, and its stores and fluxes, to climate and land use change? (3) How can improved understanding of the Critical Zone be used to enhance ecosystem resilience and sustainability, and restore ecosystem function?

Intensive field measurements at the observatories will provide the data to guide process understanding to develop models that explain Critical Zone evolution, to forecast possible future states, and to guide land-use decisions. All of the CZOs have modeling components, though a wide range of approaches is used.

2.4 COMMON MEASUREMENTS CONCEPTUAL FRAMEWORK AND GOALS

Although the network of CZOs has been developing to increasing levels of coordination and large efforts have been made to develop the cyber infrastructure for sharing data (e.g., Horsburgh et al., 2009; Niu et al., 2011), it is obvious that different measurement and modeling strategies are used at each site. In some cases this is appropriate and beneficial. Indeed, the CZOs must remain incubators of methodologies and innovation. However, some of the science questions require the use of identical measurement and modeling strategies across sites. This latter need is especially important as the CZO network expands globally.

Measurements at the US CZOs include a common set of variables that quantify CZ architecture and evolution; fluxes across the CZ boundaries; and, fluxes and changes in storage of the major CZ reservoirs at the catchment scale. The CZOs have recognized that many of the details of overarching science questions can best be addressed if a core set of variables is measured across the CZOs, and if those core measurements are made using the same or readily comparable methods. Thus, while each site develops and shares novel approaches to quantifying the CZ, all sites aim to make a set of cross-CZO comparable measurements. A key aspect of such "common" measurements is sampling that must be guided by site conditions and the science questions at hand, but to the extent possible should be carried out using materials and methods that are similar. The site-specific approach is based on the principal of "best technique and sampling design" for the individual CZO. The data collected are comparable with local, regional, and global monitoring efforts.

Despite this network-wide agreement, identification of essential Critical Zone variables – the data without which Critical Zone processes and functions cannot be properly understood and modeled – has so far proven to be challenging. Given the wide range of measurement activities each CZO is engaged in, the development of common sampling and measurement protocols is not a small task. Nonetheless, progress has already been made along these lines. A CZO Common Measurements working group coalesced during Fall 2012 and helped write and edit the so-called Common Measurements document available at: http://criticalzone.org/christina/publications/pub/chorover-et-al-2012-common-critical-zone-observatory-infrastructure-and-mea/. A CZO Graduate Research Group was encouraged to help determine "commonality" across the CZO network. That effort showed that all or most of the CZOs are engaged in twenty-five categories of specific instrumentation and campaign-style measurements to quantify the composition and fluxes across the land-atmosphere boundary through vegetation, regolith, and ground and stream-water through space and time. More recently, the CZO PIs concluded that the CZOs share the common view that the CZ evolves a structure that influences the storage and flux of water, solutes, sediments, gases, biota and energy; and, that by mediating these stores and fluxes, the CZ provides services that are critical to humanity. This review also concluded that science strategy at the 10 CZOs share three general questions: (1) What controls CZ properties and processes? (2) What will be the response of the CZ structure, and its stores and fluxes, to climate and land use change?; and, (3) How can improved understanding be used to enhance CZ resilience and sustainability, and restore CZ function?

Despite these efforts, the scale of measurement and methodology used across the CZOs to address societally relevant issues has not been standardized and the ability to initiate comparative studies remains an elusive goal. The list in Table 2.1 is drawn from the aforementioned Common Measurements document and includes a minimum set of processes that should be measured to adequately characterize the CZ – this important list provides a starting point from which future conversations can coalesce and evolve.

TABLE 2.1 Categories of Instrumentation and Measurements Made at the United States CZOs.

1. Land-atmosphere
   a. LiDAR datasets
   b. Eddy flux for momentum, heat, water vapor, CO_2
   c. Wind speed and direction sensors
   d. Solar radiation and temperature sensors
   e. Precipitation and through-fall samplers
   f. Wet and dry deposition samplers
2. Vegetation and associated microbiota
   a. Above- and below-ground vegetative and microbial composition
   b. Relations between ET and species composition and structure
   c. Soil/plant respiration, net ecosystem exchange
3. Soil (vadose zone)
   a. Solid phase (campaign sampling for spatial characterization)
   b. Elemental composition and mineralogy
   c. Texture and physical characterization
   d. Organic-matter content
   e. Stable and radiogenic isotope composition
   f. Fluid phase (sensors and samplers for time series)
   g. Soil moisture (sensors)
   h. Soil temperature (sensors)
   i. Soil-solution chemistry (samplers)
   j. Soil-gas chemistry (samplers/sensors)
   k. Rates of infiltration and groundwater flow
4. Saprolite and bedrock (saturated zone)
   a. Solid phase (campaign sampling for spatial characterization)
   b. Petrology and mineralogy
   c. Elemental-composition and organic-matter content
   d. Texture and other physical and architectural traits
   e. Fluid phase (sensors and samplers for time series)
   f. Potentiometric head and temperature (sensors)
   g. Groundwater chemistry (samplers/sensors)
   h. Gas chemistry (samplers/sensors)
5. Surface water
   a. Discrete and instantaneous discharge (flumes, weirs, with water quality sensors)
   b. Channel morphology
   c. Stream-water chemistry, dissolved and suspended (samplers/sensors)
   d. Sediment and biota (samplers/sensors)

2.5 INTERNATIONAL CZ PROGRAM OF RESEARCH AND EDUCATION

Since the initiation of conversations regarding an interdisciplinary effort to study the CZ, CZ researchers have recognized the need to engage colleagues globally. Beginning in 2007, the US NSF CZ International Scholars program funded 54 graduate and post-doctoral students to pursue CZ research in Europe. Additional students have been supported to attend training workshops in Crete and Iceland in that time frame. In Europe during 2007–2009, Critical Zone researchers were initially organized under the acronym SoilCritZone, a European Commission-funded project. That project facilitated a series of meetings and workshops that led to a report to policy makers on soil sustainability in Europe. Eventually a subset of these European researchers organized and developed a proposal to the European Commission that was funded, and the SoilTrEC project, the European counterpart to the US CZO program, began in January 2010. Back in the United States, by late 2009 the need for coordination of a variety of cross-CZO activities became necessary, and NSF funding was secured midway through 2010 to support such an effort. NSF support for US coordination of international collaborative activities, primarily between the US CZOs and the SoilTrEC project, was obtained at approximately the same time.

An international workshop was convened in November 2011 at the University of Delaware to develop an international CZ science agenda for the next decade. Eighty-nine scientists from 25 countries attended the meeting and debated and refined 6 key science questions and developed these into research hypotheses and framework experimental designs, in order to move a 10-year agenda forward (final workshop report available at: http://www.czen.org/files/czen/Sustaining-Earths-Critical-Zone_FINAL-290713.pdf). A common feature of the experimental design was the establishment of CZO networks along planetary-scale gradients of environmental change (Fig. 2.34), for example, gradients of climate and intensity of land use (Banwart et al., 2013).

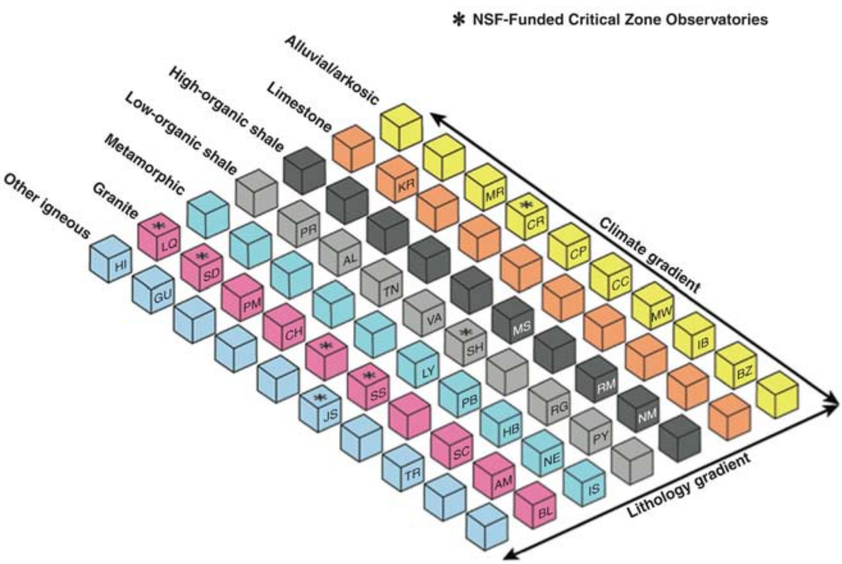

FIGURE 2.34 CZOs developed on different continents may still be understood within an organizational framework as shown schematically here. The sites are positioned along environmental gradients, in this case of lithology and climate. By understanding sites within these gradients we will evaluate the full range of Earth-surface conditions and processes.

Meeting participants recognized that international networks of CZOs offer enormous potential to globally integrate basic science with innovation in human adaptation to rapid and intensive environmental change. Achieving this vision requires a transformation in the ambition and integration of CZO science agendas worldwide. The CZO aim is to understand the resilience and vulnerabilities of the CZ, and to formulate interdisciplinary solutions to sustaining the CZ for future generations. To advance this global project requires continued development and implementation of the Delaware plan for a coordinated international program of CZO research and education.

2.6 CONCLUSION

The central idea of CZ science has captured the imagination of scientists worldwide: to learn to measure the panoply of processes occurring today in the CZ and to relate these to the history of these processes that is recorded in the soil and rock record. The idea of CZ science has also crossed agencies within the US federal government: ideas about the CZ are now driving some research within the Department of Energy's Terrestrial Ecosystem Science program, and in the US Geological Survey. The scientific community must learn to forecast CZ processes using both observation and computational simulation. New CZ knowledge will support quantitative models across scales of space and time to determine how the CZ has transformed in the Anthropocene, and to project how the CZ will continue to transform into the future. CZ science offers enormous potential to integrate basic knowledge of Earth's surface with sustainable adaptation to ongoing rapid and intensive land-use and climate change. CZOs are the environmental laboratories from which this knowledge will be gained.

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