From Roots to Canopy: An Evolving Framework for Critical Zone Education and Outreach

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ABSTRACT

Critical Zone (CZ) science provides an integrative framework for understanding the Earth as an interconnected system spanning from the vegetation canopy through soils and weathered rock to groundwater. While the CZ concept has become foundational within earth and environmental sciences, it remains unfamiliar to many educators, students, and community audiences. This paper presents the evolution of over a decade of education and outreach (E&O) efforts developed through two sequentially NSF-funded research initiatives, IML-CZO and CINet, focused on intensively managed agricultural landscapes in the midwestern United States. We present an evolving E&O framework, metaphorically represented as a "CZ tree," in which scientific research forms the roots that support the growth of integrated E&O branches. This framework was guided by five core goals: advancing CZ understanding, strengthening technical skills, promoting interdisciplinary learning, engaging diverse audiences, and fostering career development. Goal-directed activities included K–12 curriculum development, undergraduate and graduate research-based coursework, professional development workshops, public-oriented data visualizations, stakeholder engagement events, participatory watershed decision-support tools, and the creation of a student-led dialogue forum. Formal evaluation of select activities demonstrated measurable gains in teacher, student, and public understanding of CZ concepts and decision-making capacity among watershed stakeholders, whereas sustained participation across other initiatives facilitated long-term capacity building and professional growth. Collectively, the IML-CZO and CINet projects demonstrate how integrating E&O into active research networks can strengthen environmental literacy and stewardship through the development of durable actions that extend CZ science into classrooms, communities, and decision-making spaces.

Keywords: critical zone, environmental literacy, education, outreach, research, stewardship

Introduction

Critical Zone science provides an integrative framework for understanding the Earth as an interconnected environmental system. Critical zone is defined as the zone stretching from the top of the vegetation canopy down through the soil, rock, sediment, water, air, organic matter and organisms to the depth at which meteoric water is in chemical equilibrium with minerals [Anders et al. 2018]. Within this dynamic layer of the Earth, processes such as soil formation, water filtering, nutrient cycling, and vegetation growth sustain ecosystems and human societies. The concept of the "CZ" emphasizes the interdependence of the processes that dominate these physical, chemical, and biological systems, highlighting how changes in one system component can propagate throughout the entire CZ (NRC, 2001; Brantley et al., 2007).

To advance the understanding of the CZ, the National Science Foundation (NSF) launched the Critical Zone Observatories (CZOs) program in 2007 to foster interdisciplinary research, which evolved into the Critical Zone Collaborative Network (CZCN) in 2019 to strengthen collaboration across institutions and earth science disciplines (Anderson et al., 2008). As the CZ research matured, it became clear that understanding the CZ requires not only scientific inquiry but also effective translation of CZ knowledge into education and outreach (E&O). By connecting learners, educators, and communities with active research, CZ science becomes a platform for systems thinking, place-based learning, and environmental stewardship.

Although the CZ framework has been widely adopted within environmental and social sciences (Brantley et al., 2007; Banwart et al, 2013; Richardson & Kumar, 2017; Minor et al., 2020; Wymore et al., 2023; Naylor et al., 2023 a,b; Chein et al., 2024, Richter et al., 2024), CZ as an important environmental concept has largely been confined to the scientific community. Introduced beyond this community, the term often elicits curiosity or confusion rather than understanding. These mixed reactions underscore the challenge of integrating the CZ construct into broader mainstream conversation (Tague & Brandt, 2023; Singha et al., 2024). E&O provides the means to bring CZ science into public consciousness, helping learners recognize the relevance of human actions on interconnected CZ systems. Early efforts to introduce CZ concepts in university curricula (White et al., 2018) have shown promise, but broad, multi-level strategies are required to integrate formal, informal, and community-based education. Embedding CZ concepts in lived experiences allows learners to see themselves as active participants in sustaining the natural systems around them, fostering environmental literacy and stewardship.

The purpose of this paper is to illustrate how scientific research about the CZ can serve as the roots of environmental education and outreach (E&O) and how E&O activities can facilitate societal understanding of environmental science. In doing so, it synthesizes over a decade of evolving integration among research, education, and outreach efforts from two NSF-funded projects: the Intensively Managed Landscapes Critical Zone Observatory (IML-CZO; 2013–2021) and the Critical Interface Network (CINet; 2020–2026). The sections that follow trace the evolution of E&O within these projects, describe the framework's structure, and highlight key activities, showing how the roots of environmental research support education and outreach that facilitates broader public understanding of the CZ.

Materials and methods

The Education and Outreach Framework

Since 2013, the University of Illinois Urbana-Champaign (UIUC) has led a multi-university collaboration that resulted in two NSF-funded projects: IML-CZO (2013–2021) and CINet (2020–2026). Both projects focused on intensively managed agricultural landscapes in the midwestern United States, where human activities have substantially altered natural soil, water, and biogeochemical systems. E&O were central components of both efforts, with the overarching goals of strengthening public understanding of the CZ and highlighting the relevance of CZ science for environmental decision-making and resource management.

From the beginning, the E&O framework was grounded in the principle that scientific research provides the foundation for E&O. Authentic, ongoing research informed all educational activities, ensuring that learning experiences reflected real-world environmental concepts, challenges, and contemporary scientific inquiry. Addressing issues such as soil degradation, nutrient loss, and water quality in intensively managed agricultural landscapes requires not only new science, but also an informed and engaged public capable of understanding the societal relevance of that science.

While the foundational principles and aims of E&O were clearly articulated, specific activities and pathways remained flexible. As a result, E&O initiatives evolved adaptively through regular and sustained collaboration between scientists and E&O specialists. Guided by shared goals (Table 1), activities responded to emerging scientific insights, partner capacity, and community needs. This flexible approach allowed E&O efforts to grow organically while remaining rooted in the core mission of integrating research, education, and outreach.

During the project period, a variety of initiatives emerged, including workshops, university courses, K-12 curricula development, professional development opportunities, and community engagement platforms. What began as individual, opportunistic efforts gradually coalesced into a robust, interconnected E&O framework that became deeply intertwined with the research rather than peripheral to it. The culmination of this 12-year evolution can be conceptualized as a tree with (Figure 1): roots embedded in CZ Earth-system research, a trunk representing integration and synthesis, and branches and canopy symbolizing diverse, tangible E&O activities that engage learners, educators, and communities.

Table 1. General Goals of Education and Outreach
1. **Advancing understanding of evolving CZ science:** Empowering learners to grasp CZ processes and their societal implications.
2. **Enhancing technical skills:** Offering hands-on training in advanced tools and methodologies to prepare students for careers in environmental science and research.
3. **Promoting interdisciplinary learning:** Bridging disciplines such as hydrology, ecology, biology, geology, physical geography, geochemistry, and modeling and data science to tackle complex socio-environmental challenges.
4. **Engaging diverse audiences:** Extending CZ science to educators, community stakeholders, policymakers, and the broader public.
5. **Fostering environmental literacy and facilitating career development:** Creating opportunities for students, scientists, educators, and professionals to advance in their chosen fields.

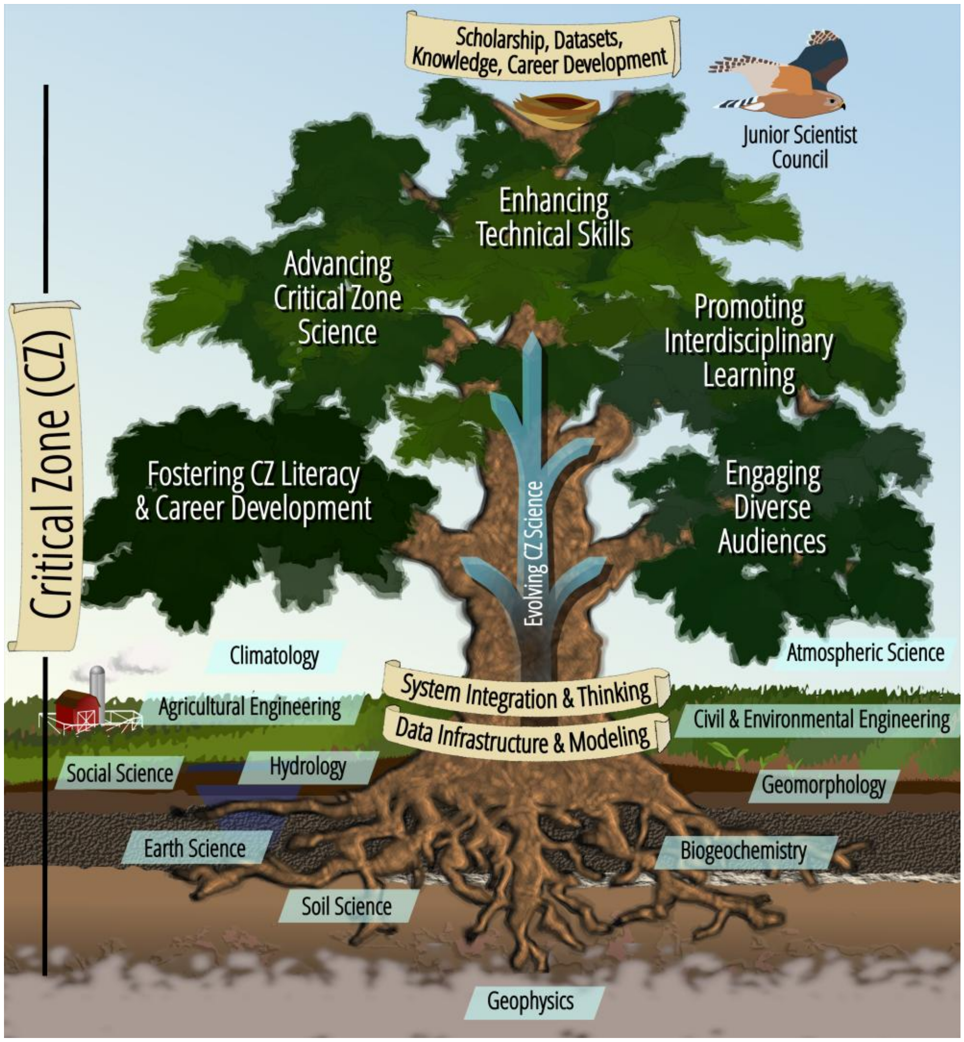

Figure 1. The Critical Zone (CZ) Tree Framework: a dual-purpose model connecting scientific roots to the evolving CZ trunk supporting five education & outreach (E&O) branches.

Table 2. Selected activities from the IML-CZO & CINet E&O spectrum.

Activity	Activity Title	Framework Goal	Development Timeline	Development Team	Participants
1	Translating CZ Research into K–12 Curriculum	Fostering CZ literacy	2022-2025	2	3000 & ongoing
2	Facilitating Learning about Humans and River Systems	Promoting interdisciplinary learning	2013-2025	1	76 & ongoing
3	Integrating Soil Biogeochemistry into Higher Education	Enhancing technical skills	2016-2020	2	25 & ongoing
4	Data Visualizations	Enhancing technical skills	2024-2025	5	20 & ongoing
5	Building Technical Capacity through CZ Workshops	Fostering career development	2015-2024	21	190
6	Informal Professional Development for Students and Researchers	Fostering career development	2014-2025	6	308
7	Sharing CZ Datasets and Communicating Findings to Research and Land Management Audiences	Engaging diverse audiences	2014-2025	11	1 county; 10K+ public
8	Data and Information Platform for Collaborative Watershed Planning	Engaging diverse audiences	2015–2017	12	110 per/session; 220 total so far
9	Early Career Scientists Council	Fostering career development	2020-2025	17	828 YouTube viewers (ongoing), 30+ students in group activities
10	Networking with International CZ Observatories and CZ Clusters	Enhancing technical skills, fostering career development.	2015 & 2020-2025	15	250

Activities: translating goals into action

Building from the scientific roots and educational goals as branches of the CZ tree framework, the IML-CZO and CINet initiatives produced a canopy of E&O activities that reflect how foundational research inspired pathways for teaching, learning, and engagement (Table 2). These activities matured into a coordinated, interconnected system supporting and impacting students, educators, and community partners. The following sections highlight key activities, illustrated by the E&O tree framework.

Educational Activities:

Activity 1: Translating CZ Research into K–12 Curriculum: A Model for Sustained Integration

Through the CINet collaboration, the National Great Rivers Research and Education Center (NGRREC) led the development of a modular, standards-aligned K–12 curriculum translating active CZ research into inquiry-driven classroom experiences. Grounded in ongoing IML-CZO and CINet research on soil health, watershed processes, and land-use management in intensively managed Midwestern landscapes, the six-unit curriculum (Figure 2) invites students to engage directly with the questions, methods, and evidence used by CZ scientists. Rather than presenting CZ science as static content, the curriculum positions students as investigators who ask questions, collect data, analyze patterns, and construct explanations about the coupled soil–water–atmospheric system shaping their communities.

The curriculum employs the 5E instructional model (Bybee et al. 2006, Bybee 2015) to support place-based, story-driven learning that integrates science, data analysis, and creative expression. Students engage in hands-on investigations such as soil and water sampling, data interpretation, and model-building, using real or simulated datasets derived from CZ research. Three of the six units are explicitly anchored in active IML-CZO and CINet research projects, allowing students to explore authentic scientific questions related to nutrient cycling, sediment transport, and watershed-scale processes. Through these experiences, learners develop systems-level thinking by examining how local environmental observations connect to broader regional and global processes within the CZ.

Curriculum development followed an iterative collaborative design approach that brought together CZ researchers, education specialists, and regional K–12 teachers. Lessons were piloted through classrooms, teacher professional development workshops, and community outreach events, generating formative feedback on student engagement, inquiry flow, and instructional feasibility. This collaborative refinement process resulted in a flexible suite of lessons designed for upper elementary, middle, and high school contexts, with scaffolding supporting diverse classroom needs and maintaining scientific authenticity. Across grade levels, the curriculum emphasizes exploration and sense-making, helping students develop evidence-based reasoning and a deeper understanding of environmental interconnections.

Figure 2. Overview of CZ in the Classroom units. Each unit has an elementary, middle, and high school equivalent.

Professional educator development was integral to this effort. Each year, NGRREC hosted workshops either on-site or at education-focused conferences covering one or multiple CZ focused units or lessons. During these sessions, teachers received detailed instructional guides and ongoing mentorship, strengthening both their CZ content knowledge and their confidence in facilitating inquiry-based learning. Place-based activities such as creating watercolor paints from locally sourced glacial sediments provided educators with tangible ways to connect geologic and soil processes to creative classroom practice. By modeling inquiry alongside teachers, E&O specialists helped translate complex scientific concepts into accessible investigations that could be sustained beyond the initial workshops.

Through embedding authentic research questions and datasets into classroom investigations and professional learning, an inquiry-centered model for engaging K–12 learners with CZ science was established. This multi-faceted, adaptable curriculum model emphasizes sense-making, systems thinking, and place-based inquiry, demonstrating how active environmental research can be meaningfully integrated into formal education settings.

Activity 2: Facilitating Learning about Humans and River Systems: A Model for Authentic, Research-Based Instruction

As part of the IML-CZO and CINet collaborations, CZ concepts were integrated into an advanced Geography and Geographic Information Science (GGIS) course at the UIUC, *Humans and River Systems*. The course engages upper-level undergraduates and graduate students across disciplines to explore how human activities shape the geomorphological and ecological dynamics of river systems.

Offered five times during the lifespan of the two projects (2013, 2015, 2019, 2021, 2024, 2025), *Humans and River Systems* has attracted students from a wide range of majors, including geography, geology, ecology, civil and environmental engineering, landscape architecture, and urban planning. This interdisciplinary composition mirrors the collaborative nature of CZ research itself, where understanding complex systems depends on multidisciplinary perspectives and expertise.

The course structure models an applied, research-centered learning experience. Organized around a project-based format, students work in interdisciplinary teams that function like those in an environmental consulting agency. Each team, led by a graduate student, identifies a research problem related to human–river interactions, designs an approach to investigating the problem, collects and analyzes relevant data, and presents both written and oral reports on their findings. More than half of class time is devoted to this collaborative, multi-discipline research process, fostering authentic engagement with scientific inquiry and data-driven problem solving.

Some projects have directly aligned with the IML-CZO and CINet research, while others have expanded to broader themes in watershed management, sediment transport, and human-induced change in river systems. Across five course offerings, students have completed 21 research projects on topics ranging from the influence of flow modification on Asian carp populations threatening the Great Lakes to changes in river-channel form associated with agricultural land use.

Activity 3: Integrating Soil Biogeochemistry into Higher Education: Cultivating Roots of CZ Understanding

Courses in Soil Biogeochemistry at Purdue University and the University of Oklahoma have incorporated CZ science, providing students with direct exposure to its concepts and applications. Originating during the IML-CZO and CINet projects, these courses engage graduate students and upper-level undergraduates in understanding the dynamic interactions among biological, chemical, and physical processes that shape soil systems and by extension, the broader CZ.

Foundational principles of soil biogeochemistry are introduced exploring how soils support ecosystems, influence agricultural sustainability, and mediate carbon cycling and climate interactions. Students examine how natural and anthropogenic forces alter soil function and resilience across temporal and spatial scales relevant to CZ development. By combining conceptual learning with hands-on experimentation, the course highlights soils as both a record and regulator of Earth-CZ system processes.

Students gain experience with a suite of analytical tools central to CZ research, including stable isotope mass spectrometry, analytical pyrolysis gas chromatography, and elemental analysis. They also conduct field and lab work to retrieve and process soils for biogeochemical analysis, strengthening their skills in data collection, critical thinking, and systems-based inquiry. Since 2014, the course has been offered six times (2014, 2016, 2018, 2020, 2023, 2025), consistently drawing students from geography, geology, agronomy, civil and environmental engineering, and landscape architecture.

The course intentionally progresses from theory to active application learning. The first half provides grounding in the fundamentals of soil biogeochemistry, while the second half immerses students in research-driven projects using datasets from IML-CZO, CINet, or related initiatives. Working in interdisciplinary teams, students formulate hypotheses, analyze data, and interpret findings, culminating in written research prospectuses and final presentations. Instructors serve as mentors throughout this process, modeling collaborative inquiry and scientific communication practices that mirror the broader CZ research community.

During the 2020 COVID-19 pandemic, the course evolved to incorporate open-air instruction and field-based lab activities at Purdue's agricultural research stations. This iteration introduced the Pacha Kit, a soil health testing toolkit CINet members and colleagues, modeled after USDA and McKnight Foundation recommendations, for international CZ research in Peru with partners at the Universidad Nacional de San Agustin de Arequipa. The kits, illustrated in Figure 3, feature 15 field and lab assessments addressing physical, biological, and chemical soil properties. Student teams each specialized in one dimension of soil health then collaboratively integrated their results to construct a holistic soil health index that reflected varying levels of agricultural management. This experiential format not only maintained academic rigor during pandemic disruptions but also deepened students' understanding of systems-level soil assessment.

Within the E&O tree framework, the UIUC and Purdue courses represent major limbs of the educational branches and are grounded in CZ science. They provide models for and demonstrate how translating research into experimental learning fosters curiosity, technical competence, and systems thinking, which are key values that advance interdisciplinary education across the CZ network.

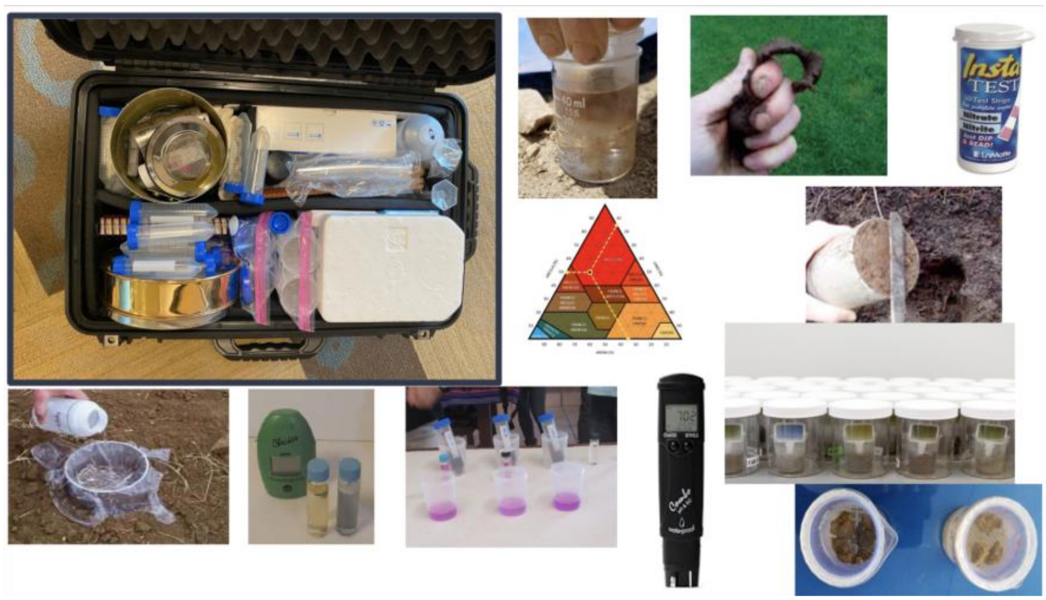

Figure 3. Photomontage of the Pacha Kit and some of the associated soil tests

Activity 4: Data Visualizations: Translating Data into Educational Insight

Through a collaboration with the National Center for Supercomputing Applications (NCSA) at UIUC, an educational data visualization was developed to make complex CZ processes visible and comprehensible to diverse audiences. The 3-minute public-oriented video illustrates land–atmosphere interactions within intensively managed landscapes. Drone footage collected by NGRREC in 2024 was integrated visually with time-series datasets from a flux tower in the Upper Sangamon River Basin landscape.

The short visualization highlights how flux tower sensors monitor carbon dioxide uptake by crops during photosynthesis and water vapor release through transpiration. The interplay between the processes of carbon uptake and transpiration, influenced by weather, soils, and vegetation, is highlighted. The video ultimately reveals to the public how small-scale vegetation and soil processes have significant regional and watershed-scale impacts on carbon and water budgets. Observations like these inform predictive models and agricultural management, linking local field data to larger-scale climate and land-use dynamics.

By blending empirical data with high-resolution imagery and advanced modeling, the visualization transforms abstract data into a dynamic learning tool that promotes systems thinking and environmental literacy. Developed through close collaboration between domain scientists and visualization specialists, the project also serves as an educational process by training researchers in effective science communication, interdisciplinary teamwork, and public engagement.

The final product, freely available on YouTube (Goodwell, 2025), exemplifies how visual communication can act as a branch joining active research and public understanding, helping learners grasp the interconnected and multi-scalar nature of CZ systems. In the E&O tree framework, this impactful research visualization for the public represents a creative, outward-reaching branch that is rooted in science and designed to engage the broader ecosystem of learners and stakeholders.

Activity 5: Knowledge Fusion — Building Technical Capacity through CZ Workshops

Several workshops focused on CZ researchers and students were developed as part of the IML-CZO and CINet projects, which served to link between CZ core disciplines, foster open science and data practices, strengthen collaboration, and provide hands-on skills development. These workshops were co-organized by project team members, often collaboratively with other CZCN groups or international partners.

IML-CZO scientists and graduate students led a 3-day workshop at the UIUC titled "Critical Zone Observatory Modeling Institute", focused on eco-hydrologic modeling of vegetation and surface-subsurface interactions using high-performance computing. This workshop involved 30 participants from 12 institutions and provided participants with skills in high resolution modeling and understanding of complex CZ processes. The workshop also promoted collaboration and innovation in model development and adoption of next-generation modeling techniques. Later, CINet researchers partnered with other CZCN groups to hold a 1-day workshop on CZ time-series data analysis, also held at UIUC. Each workshop involved 25 participants, including faculty, postdoctoral researchers, and graduate students representing at least 5 separate CZCN group projects. Workshops introduced topics of machine learning basics, time-series analysis techniques, information theory, and uncertainty, and provided hands-on tutorials which participants could apply to their own research datasets. Workshop materials were archived online on HydroShare (Goodwell, 2024) to remain accessible for ongoing use across the research network, ensuring that benefits extend beyond the original participants.

The workshops strengthened the "technical skills" branch of the E&O tree, demonstrating how collaborative learning environments can translate complex methods into practical tools. The effort underscores how capacity building, when grounded in authentic data and shared inquiry, forms a durable part of the educational infrastructure supporting CZ science.

Activity 6: Cultivating a Learning Community: Informal Professional Development for Students and Researchers

IML-CZO and CINet prioritized informal professional development activities as a vital component of its E&O mission, recognizing that transformative learning often occurs beyond the traditional classroom. Interactive, interdisciplinary activities modeled real-world scientific collaboration. Undergraduates, professors, and research professionals engaged in weekly project-wide research discussions, interdisciplinary seminars, hands-on field experiences, and collaborative writing groups that highlighted the breadth of CZ-science. Faculty openly deferred to one another's expertise, modeling trust and interdisciplinary collaboration. Observing this level of problem-solving, professional dialogue, and joint authorship offered all participants a compelling example of how complex environmental challenges are addressed through open, collegial teamwork.

Graduate students played central roles as mentors and team leaders, guiding undergraduates through project design, field protocols, and scientific communication, while simultaneously developing their own scientific leadership and collaboration skills. Several cross-institutional collaborations emerged from these interactions; for example, UIUC and Northwestern University graduate students jointly analyzed sediment and carbon datasets, resulting in shared research insights and co-authored major national conference presentations.

Field and research-based experiences formed another foundation of this learning ecosystem, highlighting both traditional and emerging research methods and ideas. Participants gained hands-on, practical experience through a rich suite of soil, water, and environmental sampling and data collection activities across diverse field environments. Graduate students and research professionals explained hydrologic field techniques and demonstrated both established and new technologies, providing on-site presentations of ongoing and published research. From K-12 students visiting Champaign's Fowler Farm Environmental Station to graduate students and REU (Research Experiences for Undergraduates) summer interns funded through the NSF-CZCN program, participants learned the logistics of data and sample collection. They also developed technical and data interpretation skills appropriate to their level.

Field trip reflections from upper level and graduate students underscore how the field experiences broadened their understanding of CZ research. One example was from a UIUC's Civil and Environmental Engineering class that visited various CZ research sites each year. One student noted, *"An interesting observation...was seeing how environmental conditions, such as droughts, can trigger carbon release."* They added, *"I was surprised by the precision and high temporal resolution of the…sensors."* Others were impressed by the ingenuity of the equipment, when *"introduced to equipment devised by and built from scratch with PVC and Arduino components"* by graduate students that are only a few years older than themselves. Seeing instruments built from scratch by graduate students made the science feel accessible and inspiring, showing that they too could accomplish the same. These reflections illustrate how the field experiences transformed perceptions of field research, from simple data collection to a dynamic process that integrates advanced technology, automation, and creativity. Participants realized that field science is not just about observation, but about innovation and discovery.

Many participants continued into professional pathways shaped by these experiences, progressing into graduate programs, research positions, and outreach-focused careers. REU alumni cited their fieldwork and mentorship experiences as foundational in understanding how environmental research connects to community relevance. These informal professional development activities served as the bridge between research, education, and career readiness, reframing CZ field science as a diverse, innovative, technology-driven process. By fostering creativity, inclusiveness, and collaboration, CINet empowered participants to see research as dynamic and impactful. This experience has inspired many to pursue graduate studies, research careers, and outreach roles, demonstrating the enduring impact of intentional, informal professional development.

Outreach Activities

Activity 7: Threading Knowledge Pathways: Communicating Findings and Sharing CZ Datasets with Research and Land Management Audiences

Translating CZ research into actionable knowledge for communities has been a defining goal of the CINet initiative. Through conference presentations and a series of outreach and engagement events, members of the CINet project facilitated the direct application of CZ data to watershed planning and land management decisions in central Illinois.

Field demonstration days at the CINet RiverLab and River Sediment site in Monticello, Illinois provided city officials, regional planners, landowners, and agricultural stakeholders from communities with the opportunity to see CINet's research efforts in action. Sharing the CINet water quality and streamflow data as well as discoveries based on these data informs evidence-based management strategies and fosters iterative dialogue between researchers and local decision-makers.

Outreach efforts also included quarterly to annual presentations to regional stakeholder groups, such as the Illinois Farm Bureau County Field Days and the Heart of the Sangamon Ecosystem Partnership, as well as at professional forums including the Illinois Lake Management Association Conferences, the Illinois Drainage Districts Annual Conference, and the University of Illinois Extension McLean County Master Watershed Steward program. At the Illinois Farm Bureau field day for Piatt and surrounding counties, CZ concepts and CINet research were presented in the context of promoting sustainable watershed and agricultural practices. This event was attended by more than 50 farmers and stakeholders. A handout with additional project resources and website links further promoted the research.

CINet research data including hydrologic, nutrient, and sediment datasets were also provided directly to the City of Decatur to inform development of the Upper Sangamon River watershed management plan. Collectively, these efforts represent the expansion of the E&O canopy into communities by bridging scientific discovery with practical decision-making and fostering ongoing engagement among researchers, regional stakeholders and community decision makers.

Activity 8: Informing Decision Makers: Data and Information Platform for Collaborative Watershed Planning

The CINet data platform evolved from a simple data repository into an integrated digital ecosystem supporting community engagement and collaborative watershed planning. Initially conceived as an internal system for managing real-time field data from experimental test sites, the platform grew to include interactive visualization tools designed for non-expert users living and working within the studied watersheds.

A partnership between IIHR-Hydroscience & Engineering, The University of Iowa (UI) with the U.S. Army Corps of Engineers' Institute for Water Resources expanded this effort into a full-fledged, web-based decision-support system that combines scientific data, modeling outputs, and participatory simulation (Sermet et al., 2020; Teague et al., 2021). The resulting prototype for the Cedar River Watershed Platform included four interrelated modules (Xu et al., 2020):

- Watershed Characterization: a comprehensive data repository integrating hydrologic, geomorphic, and land-use information.
- Watershed Planning Tools: multi-domain models for simulating land management and hydrological scenarios.
- Serious Gaming Environment: a competition-based digital game interface where users explore alternative management strategies.
- Online Plan Evaluation: a framework for comparing and scoring management outcomes using standardized performance metrics.

The system structure and design specifications for the visualization and the decision-support interfaces are described in Carson et al. (2018). This system was field-tested in a Multi-Hazard Tournament (MHT), in which stakeholders, including scientists, local managers, and community members, engaged collaboratively to evaluate real-world watershed management scenarios (see Figure 4). The experience demonstrated how serious gaming (designed to simulate interactive training and education) and digital visualization can foster engagement, shared understanding, and consensus among diverse participants.

Figure 4. Multi-Hazard Tournament gaming session in Cedar Rapids, Iowa with stakeholders, including scientists, local managers, and community members.

As part of the broader outreach canopy, the data platform exemplifies how technology-enabled participation can bring communities directly into the process of science-informed decision-making (Voinov et al., 2015). It stands as a replicable model for connecting research, policy, and public learning in ways that mirror the interconnected flows of information within the CZ.

Activity 9: Early Career Scientists Council: Growing the Next Generation of CZ Leaders

Established in 2021, the CINet Early Career Scientists Council (ECSC; formerly the "Junior Scientist Council") emerged as a platform for cross-cluster engagement and professional growth among graduate students and postdoctoral researchers across the CZCN. Initially organized to coordinate webinars and foster dialogue across clusters, the ECSC quickly evolved into a multifaceted, student-driven initiative that promotes leadership, communication, and interdisciplinary collaboration, as illustrated in Figure 5. Under the guidance of senior mentors and coordination by graduate-student leaders, the Council grew into a cornerstone of CINet's E&O framework by cultivating an inclusive research culture that empowers early-career scientists to lead within and beyond the network.

ECSC expanded its focus to emphasize structured peer development. Monthly virtual meetings, originally a response to the COVID-19 pandemic, were retained for their accessibility across institutions, becoming interactive incubators for idea exchange, project coordination, and mentorship. Rotating leadership roles allowed members to develop practical and professional skills in event organization, webinar hosting, and discussion facilitation. This shared-governance model gave participants agency in shaping Council activities while building essential competencies in project management, communication, and collaboration.

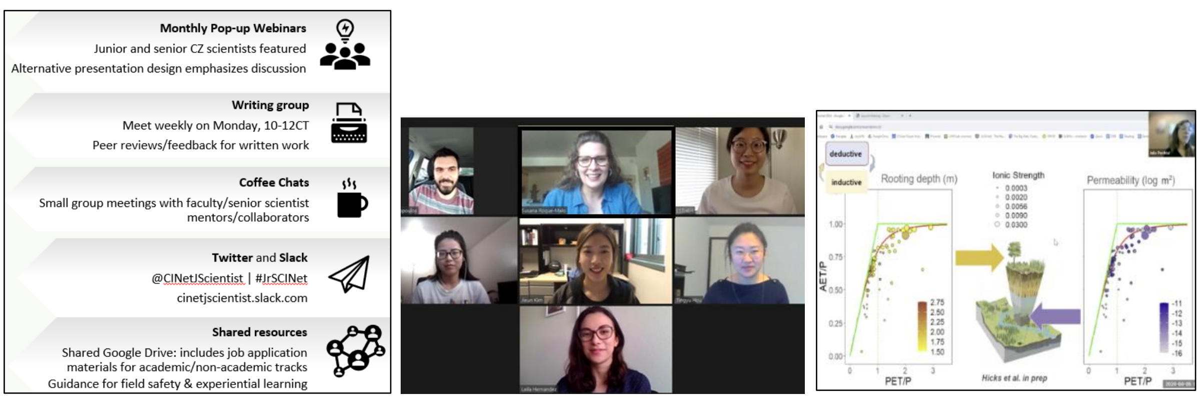

Figure 5. Early Career Scientist Council activity spectrum and samples of virtual meetings

The ECSC's hallmark initiative has been its robust webinar series, featuring speakers from across the CZ community and related disciplines. These sessions, recorded and hosted on a dedicated YouTube channel (www.youtube.com/@cinetjuniorscientistcounci9808), extend access to a global audience and strengthen interdisciplinary exchange. In parallel, faculty-facilitated writing groups have provided targeted support in scientific writing, abstract development, and peer review, creating a structured yet supportive environment for professional growth. These efforts have collectively enhanced members' ability to communicate complex CZ concepts to diverse audiences, reflecting the ECSC's broader goal of linking research excellence with science communication capacity.

Now in its fifth year, the ECSC continues to thrive as a key branch of CINet's educational and professional ecosystem. Sustained student-driven activities have enriched both individual career development and the collective resilience of the CZ community. Functioning as the upper canopy of the E&O tree, the ECSC represents a living model of how early-career empowerment, mentorship, and communication training can sustain the long-term vitality and inclusivity of the CZ research enterprise.

Activity 10: Crossing Knowledge Frontiers: Joining International CZ Observatories & US CZCN

Formal CZO research was launched in 2007 by the USA NSF, which quickly became adopted as a programmatic research initiative within Europe, the United Kingdom, and China. Over the course of the IML-CZO and CINet lifecycle, international CZ science engagement with China, UK, France, India, Peru, and United Kingdom was an important facet of scientific collaboration.

The first international E&O activity of the IML-CZO program occurred in 2015 at co-convened a workshop and conference "CZ Science, Sustainability, and Services in a Changing World" with the U.S.-China EcoPartnership for Environmental Sustainability, and the Working Group on Organic Matter Dynamics in the CZO Network, at Purdue University. The gathering brought together over 150 leading researchers and their students, with one third traveling from China, to share the latest science related to terrestrial ecosystem function and vulnerability, and to discuss and debate options for sustainable use of natural resources in the context of the CZ. The conference attracted broad institutional participation with 22 U.S., 1 U.K., and 16 Chinese academic and research institutions represented.

Members of the newly funded China CZO Network were also in attendance and engaged in discussions to promote multi-national, Cross-CZO research. The conference included distinguished invited lecturers, as well as panel discussions, workshops, and opportunities for informal networking. Delegations completed cross-institutional, bi-national education agreements and initiated plans for follow-up CZO meetings in China.

The U.S. National Science Foundation established the Critical Zone Collaborative Network (CZCN) in 2019, focusing on major scientific questions about the structure, function, and processes of the CZ through integrated monitoring and research (NSF, 2019). CZCN was organized into nine thematic clusters, each focused on a different aspect of CZ science across a range of geological, climatic, and land-use settings (Boyer, 2025). CZCN established a cross-cluster E&O Working Group early in the program to coordinate and enhance outreach efforts across its thematic clusters. During the CZCN ongoing activities, new initiatives created by various CZCN clusters were highlighted and critically assessed before to become scholarly contributions in the embryonic developments in the CZ E&O area (Parish & Anderson, 2022; Arora et al., 2023; Perdrial et al., 2023). The CINet participated actively with the CZCN E&O working group to align strategies and exchange practices related to K-12 education, educator professional development, and informal community-based learning. These regular interactions and the culminating CZCN all-hands workshop held in 2025 mutually benefitted the cross-cluster collaboration and contributed to substantiation of the CZCN identity.

Results

This section summarizes impacts from the IML-CZO and CINet E&O framework, organized by evaluation approach. Activities 1 (*CZ in the Classroom*) and 8 (*Multi-Hazard Tournament*) include formally assessed outcomes and are presented with quantitative evidence of impact. The remaining activities highlight sustained participation, professional growth, and long-term capacity building across educational stages, with impact demonstrated through continued implementation, participant progression, and the development of enduring networks. Together, these outcomes reflect both rigorously measured results and broader, cumulative impacts of the E&O framework.

Formally Evaluated Activities

Impact of Translating CZ Research into K–12 Curriculum

The *CZ in the Classroom* curriculum (Activity 1) has become one of the most durable outcomes of the IML-CZO and CINet E&O framework, transitioning from pilot implementation to sustained integration within NGRREC's education portfolio. Evaluation findings demonstrate both measurable outcomes and long-term program viability. As documented by New Growth Group (2025), over 50 teachers representing 20 schools participated in professional development workshops such as *Roots to Rivers* and *Paint with the Prairie*, collectively reaching more than 800 students across urban and rural communities. Participating educators reported significant gains in confidence teaching environmental science and improved understanding of CZ concepts. In addition, fifteen classroom field kits were distributed to support continued place-based investigations beyond workshop participation, strengthening the curriculum's capacity for lasting classroom impact.

Additional findings from *CZ in the Classroom* (New Growth, 2025) indicate measurable increases in student understanding of Earth-system interconnections and positive shifts in teacher perceptions of the value of place-based learning for strengthening environmental literacy. A multi-day teacher workshop that served as a focused evaluation cohort revealed substantial pre/post gains across all eight assessed content areas, with average increases ranging from +1.2 to +2.8 points on a 5-point scale (Figure 6). The most significant gains occurred in understanding carbon dioxide flux in agricultural systems, critical interfaces, and CZ science as an integrated framework for interpreting environmental processes.

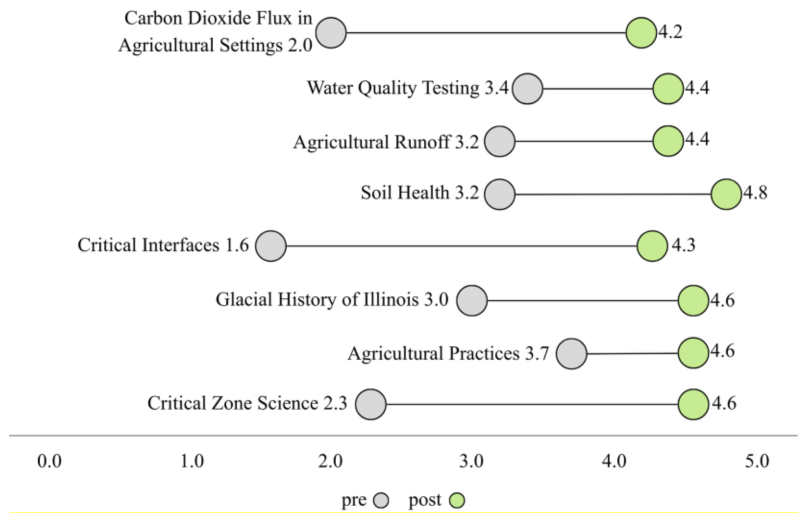

Figure 6. Change in teacher familiarity scores across eight CZ in the Classroom workshop topics, based on pre/post surveys from the teacher focus group: carbon dioxide flux in agricultural systems, water quality testing, agricultural runoff, soil health, critical interfaces, glacial history of Illinois, agricultural practices, and CZ science.

Workshop outcomes further highlight the effectiveness and reach of the curriculum. *Roots to Rivers: Exploring the Soil-to-Stream Connection* engaged 32 teachers from 14 schools; despite limited prior familiarity with CZ concepts, 100% of surveyed participants (n = 15) reported increased understanding of Illinois geology and identified the hands-on investigations as directly applicable to classroom instruction. During *Science on the Sangamon*, eight K–12 educators conducted water-quality testing and analyzed real-time RiverLab data, strengthening their ability to connect classroom learning with active environmental research. In *Paint with the Prairie* classroom trainings, 10 teachers demonstrated statistically significant gains in familiarity with CZ concepts, with increases of up to 2.3 points on a 5-point scale, and expressed strong enthusiasm for the art-integrated, inquiry-driven approach (Figure 7).

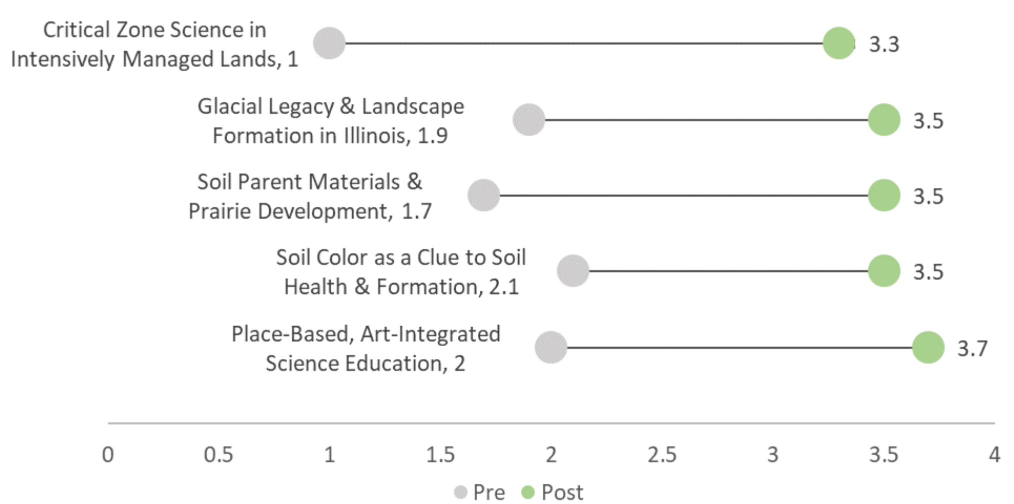

Figure 7. Changes in teacher familiarity with *Paint with the Prairie* workshop topics.

The adoption of CZ in the Classroom into NGRREC's ongoing education and professional development programming ensures continued implementation beyond the CINet funding period. Continued workshop delivery, paired with a formal curriculum study, provides a clear structure for sustained refinement, expanded educator engagement, and continued evaluation of student learning outcomes.

Stakeholder Engagement and Decision Support Outcomes

Outreach efforts expanded the E&O canopy through direct engagement with community stakeholders and internationally. A notable example is the *Multi-Hazard Tournament* (Activity 8), which demonstrated the value of participatory modeling for decision-making related to watershed management planning. Post-event evaluation showed that 62% of participants found the tournament helpful for identifying strengths and weaknesses of adaptation options, and 52% reported improved problem-solving skills for evaluating costs and trade-offs among watershed management strategies (Table 3).

Table 3. Quantitative evaluation of the multi-hazard tournament for problem-solving (n=21).

Statement (scale 1-3 from no, to maybe, to yes)	No (%)	Maybe (%)	Yes (%)	Mean (Stdev)
Identifying costs and trade-offs for various best management practice strategies	28.6	9.5	61.9	2.3 (0.91)
Identifying strengths and weaknesses for best management practice strategies	19.1	28.6	52.4	2.3 (0.80)
Developing hazard mitigation plans for flood, drought, and water quality hazards	19.1	33.3	47.6	2.3 (0.78)
Evaluating financial costs for solving problems	23.8	42.9	33.3	2.1 (0.77)
Conducting flood, drought, and water quality vulnerability assessments	33.3	38.1	28.6	2.0 (0.80)

Non-Formally Evaluated Activities

Cultivating Professional Growth Through Longitudinal Learning

Across IML-CZO and CINet, students, educators, and researchers were connected through a continuum of authentic learning experiences spanning undergraduate field assistants, graduate mentors, technical trainees, and early-career leaders. Long-term engagement enabled participants to deepen expertise, confidence, and professional identity through repeated exposure to interdisciplinary collaboration.

This longitudinal pathway was especially evident in *Informal Professional Development for Students and Researchers* (Activity 6) where informal professional development including field sessions, interdisciplinary seminars, and collaborative writing groups were integrated with hands-on research experiences for REU interns and other students. REU participants worked alongside graduate mentors to conduct soil, water, and river sampling, gaining practical experience in hydrology, geomorphology, and environmental chemistry. Graduate students simultaneously strengthened leadership and mentoring skills through supervision of field activities, data analysis, and communication of findings. These layered experiences provided participants with a genuine view of how interdisciplinary environmental science operates in practice and fostered lasting professional networks.

Formal coursework further reinforced this developmental pipeline. Courses such as *Humans and River Systems* (Activity 2) and *Soil Biogeochemistry* (Activity 3) engaged students in field and laboratory investigations, analysis of real datasets, and development of conceptual models linking soil and river processes to broader Earth systems. By situating student learning within the context of real-world research challenges, these courses exemplify how higher education can cultivate systems thinking, interdisciplinary collaboration, and applied problem-solving skills. In doing so, these courses reinforce one of the central branches of the growing E&O framework: grounded, inquiry-based learning rooted in the same scientific “soil” that nourishes CZ research.

Many undergraduates who participated in these courses progressed into graduate study, applied research, or policy-focused careers, demonstrating the role of experiential coursework in bridging academic learning and professional practice. These academic courses also demonstrate the long-term impact of embedding CZ science within university curricula. Several graduate students participating in the courses have gone on to careers as CZ scientists in academia, government, and the private sector, illustrating how experiential, research-integrated coursework can serve as a pipeline for future professionals in environmental science.

Professional growth was further institutionalized through ECSC (Activity 9). The ECSC evolved from a webinar-planning group into a sustained, peer-led professional network spanning institutions and disciplines. Now in its fifth year, the ECSC functions as an enduring professional infrastructure that continues to cultivate leadership capacity within the CZ community.

Participants in university courses, technical workshops, and informal professional development activities consistently reported improved interdisciplinary collaboration skills, enhanced data-analysis proficiency, and increased confidence communicating complex environmental processes. Informal professional development (Activity 6) strengthened teamwork and leadership capacity, while the ECSC (Activity 9) established a sustainable model for peer mentorship and professional advancement across institutions.

Toward a Sustainable Canopy: Lasting Evolution and Reach

The impacts of these evolving efforts extend beyond the lifespan of individual projects. By embedding E&O within established research institutions such as UIUC, NGRREC, UI, and Purdue and aligning them with regional and national education networks, CINet ensured that the programs, partnerships, and professional pathways cultivated through IML-CZO will be sustainable and continue to evolve.

The K–12 curriculum and technical workshop series now function as enduring components of a self-sustaining educational infrastructure. Similarly, the ECSC grass-root professional assembly will continue its impacts for years to come. The ECSC creates a continuum between past and future with a visible influence on the career trajectories of its alumni with past members noting that the experience helped to develop leadership skills, a research framework that integrates diverse sites, data, and approaches, and an interdisciplinary perspective that fostered a collaborative mindset. Participation in the Council shapes long-term professional philosophies and the capacity to bridge complex, multi-scalar scientific challenges.

Discussion

Cultivating an Evolving Education Ecosystem

The E&O framework developed across the IML-CZO and CINet projects illustrates how research, education, and outreach can co-evolve as a unified, regenerative system. Organized around five key original goals (hereafter referred to as the branches of the E&O tree (Table 2), the framework was comprised of multiple integrated activities (Table 4) that advanced varied forms of environmental literacy while also establishing durable pathways for professional growth and institutional transformation in the creation of the CZ tree (Figure 1). Much like the CZ itself, where biological, chemical, physical, and social processes interact to sustain continuous regeneration (NRC, 2001; Brantley et al., 2007), the E&O tree framework functioned as a living educational ecosystem: adaptive, interconnected, and self-renewing.

Table 4. Relation of Activities (column 2, Table 2) to the E&O Framework's Goals (Table 1)

Goals	Specific activities	1	2	3	4	5	6	7	8	9	10
Promoting CZ science to foster environmental literacy	*Cross-cutting curriculum*	X	X	X			X				
	Teacher training	X									
	Student education		X	X			X			X	X
Enhancing technical skills	*Familiarization with technological advancements in observations, data analysis, modeling, and AI tools*	X	X		X	X	X		X		X
	Project-based or hands-on learning modules		X	X		X	X				
Promoting interdisciplinary learning	*Bridging disciplines in a structured curriculum*	X	X	X			X				
	Translating CZ innovation in learning STEM and environmental sciences		X	X	X		X	X			
Engaging diverse audiences	*Shifting to translational science*							X	X		X
	Targeted outreach programs	X					X	X	X		X
	Community capacity building							X	X	X	
	Multi-ethnic involvement		X				X				
Facilitate career development	*Preparing the next generation of CZ scientists*		X	X		X	X			X	X
	Teacher training	X									
	Professional education						X			X	

Intellectual and Societal Impacts Through the E&O Tree Framework

Advancing Understanding of Evolving CZ science (Environmental Literacy)

The first E&O branch forms the foundation of environmental literacy by grounding abstract Earth-system concepts in place-based inquiry. Curriculum integration (Activity 1) and research-aligned coursework (Activities 2 & 3) enabled learners to investigate soil–water–atmosphere interactions using locally relevant data, fostering understanding of how environmental processes shape (and are shaped by) human activity. Place-based and inquiry-driven learning approaches have been shown to deepen conceptual understanding while increasing relevance and learner engagement (Gruenewald, 2003; Minor et al., 2020).

Rather than emphasizing content acquisition alone, these experiences cultivated interpretive skills that allow learners to connect local observations to broader environmental systems, a core element of environmental literacy and stewardship-oriented education (Hollweg et al., 2011; Richardson & Kumar, 2017).

Enhancing Technical Skills (Data Literacy and Technical Competence)

The second E&O branch advanced data literacy by normalizing hands-on engagement with complex datasets, analytical tools, and modeling approaches. Technical workshops (Activity 5), visualization initiatives (Activity 4), and field-based learning experiences (Activity 6) moved participants beyond data consumption toward interpretation and communication which is an increasingly essential competency in environmental science and policy (NASEM, 2018). Instructional and research tools such as the Pacha Kit (Activity 3) illustrate a suitable approach of combining conceptual depth, field application, and authentic research experience in an instructional and research means for cultivating the next generation of CZ scientists.

Public-oriented visualizations and participatory platforms that are freely available on YouTube (Activity 4; Goodwell, 2025) along with CINet seminars and related materials (Activity 9; CINet Jr Scientist Council, 2025), further extended these competencies to non-specialist audiences, supporting transparency and shared decision-making. Prior research demonstrates that visualization and interactive modeling can significantly enhance comprehension of complex Earth-system processes and uncertainty (McCurdy et al., 2016; Chein et al., 2024).

Promoting Interdisciplinary Learning (Systems Literacy and Collaboration)

Interdisciplinary learning emerged as a defining strength of the framework, mirroring the integrative nature of CZ science itself (Brantley et al., 2017; White et al., 2018). College-level coursework (Activities 2 & 3), informal professional development (Activity 6), and K–12 inquiry activities (Activity 1) consistently required learners to integrate hydrologic, biogeochemical, geomorphological, ecological, and social perspectives.

Through repeated exposure to interdisciplinary problem-solving, participants developed systems literacy and the ability to recognize feedback, cross-scale interactions, and emergent behavior within complex systems (Meadows, 2008; Naylor et al., 2023a). Such capacities are increasingly recognized as critical for addressing socio-environmental challenges including climate adaptation, water-resource management, and land-use planning (Wymore et al., 2023).

Engaging Diverse Audiences (Public and Stakeholder Engagement)

The fourth branch extended CZ science beyond academic settings by engaging educators, planners, policymakers, and community stakeholders (Activities 7 & 8). Participatory tools and outreach initiatives fostered shared learning and co-production of knowledge, enabling stakeholders to interpret scientific data within genuine decision-making contexts.

This approach aligns with growing evidence that community-engaged and participatory science strengthens trust, relevance, and uptake of scientific knowledge in environmental governance (Cash et al., 2003; Meadow et al., 2015; Naylor et al., 2023b). By situating science within societal contexts, the E&O framework supported societal literacy by understanding how scientific knowledge informs collective action.

Facilitating Career Development (Professional and Leadership Literacy)

The fifth goal emphasized sustained professional growth across career stages. Informal professional development networks (Activity 6) provided mentorship structures that nurtured collaboration, leadership, and communication skills among students and researchers. The ECSC (Activity 9) institutionalized this mentorship, transforming early-career participation into peer-led leadership. Through rotating leadership roles, writing groups, and international collaborations (Activity 10), participants gained practical experience in project coordination and science communication. Alumni such who attained academic positions at Handong Global University and the University of Alabama exemplify this progression, demonstrating how the council's systems-based approach equips emerging scientists for leadership in academia and applied research. This career development branch thus represents the regenerative cycle of the E&O tree, where each generation of learners becomes a mentor for the next, sustaining the growth of the CZ community.

The fifth branch emphasized sustained professional growth across career stages. Mentorship networks and peer-led leadership structures cultivated communication, collaboration, and project-management skills alongside scientific expertise. Such competencies are increasingly recognized as core outcomes of graduate and early-career STEM education, particularly in interdisciplinary research environments (Frodeman et al., 2017; National Academies, 2018).

By institutionalizing leadership development within the research network, the framework created a regenerative cycle in which emerging scientists and educators become mentors and leaders for subsequent cohorts. This structure reinforces continuity and resilience within the CZ community while aligning with calls for workforce development models that integrate technical expertise with communication and leadership skills (White et al., 2018).

What began as a collection of discrete initiatives matured into a resilient, interconnected ecosystem represented by a tree (Figure 1). The living tree of CZ E&O where ideas, people, and practices grow and co-evolve, rooted in research and extending toward broader societal understanding.

Ancillary Impacts: From Individual Growth to Institutional Integration

Across the E&O goals, ancillary impacts were realized at multiple scales. At the individual level, learners developed confidence, interdisciplinary competence, and professional identity. At the institutional level, partnerships embedded research-based education within durable organizational structures. At the societal level, outreach and participatory tools strengthened science–policy connections and community engagement. Collectively, these impacts demonstrate that the framework not only disseminated knowledge but also transformed the systems within which that knowledge circulates, an outcome consistent with prior studies of long-term research (Richardson & Kumar, 2017; White et al., 2018).

Challenges, Lessons Learned, and Future Needs

The challenges, lessons learned, and future needs identified here mirror those observed in other large, distributed interdisciplinary science networks (Cash et al., 2003; Meadow et al., 2015). Integrating E&O across a distributed research network required early coordination between research and education teams, translation of complex datasets for instructional use, and sustained engagement over long project timelines, with the COVID-19 pandemic highlighting the need for rapid adaptation to hybrid and outdoor learning environments.

Key lessons include the importance of early integration to strengthen mutual reinforcement between research and education, co-design to foster relevance and shared ownership, adaptability to expand accessibility and resilience, and community structures (peer mentorship and distributed leadership) to support continuity beyond funding cycles. Future efforts should focus on scaling evaluation frameworks, expanding digital and participatory engagement, investing in long-term mentorship infrastructure, and advancing inclusivity to enhance diversity, innovation, and the overall impact of CZ education and research.

Conclusion

The IML-CZO and CINet E&O framework demonstrates how education, outreach, and research can co-evolve as a regenerative system. Rooted in authentic science, branching through collaboration, and extending its canopy into society, the tree framework for education and outreach enhanced environmental, systems, and data literacy while cultivating enduring human and institutional capacity. Its legacy lies not only in the knowledge it produced, but in the capacity it nurtured and the ability of individuals, institutions, and communities to think, learn, and act as interconnected parts of the environmental system known as the Critical Zone.

Author Contributions

P. Kumar – outlining original draft and funding acquisition; M. Muste – writing original draft and coordination; J. Mohlman, B. Rhoads - conceptualization and writing; All authors – writing, reviewing & editing.

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Activity	Activity Title	Contributors
1	Translating CZ Research into K–12 Curriculum	J. Mohlman, E. Doerr, P. Mettler-Cherry (National Great Rivers Research and Education Center)
2	Facilitating Learning about Humans and River Systems	B. Rhoads (University of Illinois Urbana Champaign-UIUC)
3	Integrating Soil Biogeochemistry into Higher Education	T. Filley, M. E. Jimenez-Castaneda (University of Oklahoma); C. Johnston (Purdue University); E. Foster (Point Blue)
4	Data Visualizations	A.Goodwell, D. Bock (UIUC)
5	Building Technical Capacity through CZ Workshops	A.Goodwell, P. Le, K. Underwood, D. Rizzo (UIUC)
6	Informal Professional Development for Students and Researchers	E. Bauer, A. Stumpf, J. Haken (Prairie Research Institute, UIUC); B. Rhoads, A. Goodwell, C. Salas (UIUC)
7	Sharing CZ Datasets and Communicating Findings to Research and Land Management Audiences	E. Bauer, A. Stumpf, L. Keefer, H. Wennerdahl, I. Hoffman, K. Attig (Prairie Research Institute - UIUC); J. Druhan, B. Rhoads, J. Wang, A. Schmidt, P. Kumar (UIUC)
8	Data and Information Platform for Collaborative Watershed Planning	M. Muste, I. Demir; Y. Sermet, H. Xu; H. Haider (University of Iowa); A. Carson, H. Hill; J. Smith (US Corps of Engineers).
9	Early Career Scientists Council	A. Dolant, A. Moronfoye; M. Farhani; L. Hernandez; S. Roque-Malo (UIUC)
10	Networking with International CZ Observatories and CZ Clusters	T. Filley; T. Papanicolaou (USDA); D.L. Guo (CAS), S. Banwart (University of Leeds); H. Lin (Pen State University)

Disclosure statement

No potential conflict of interest was reported by the authors.

Ethical Statement

This article describes informal education and outreach activities that did not involve human subjects research or the collection of personal data.

Supplemental online material

Activity	Activity Title	Material nature	Source/Reference
1	Translating CZ Research into K–12 Curriculum	• Curriculum sample • Photo collection: Painting with Prairie (web album)	**CINet Teacher Workshop (July 2025)** www.flickr.com/photos/ngrrec/albums/72177720327555850 **Digging Into the Critical Zone: Illinois scientists and educators bring soil science to life** //outdoor.wildlifeillinois.org/articles/digging-into-the-critical-zone-illinois-scientists-and-educators-bring-soil-science-to-life
2	Facilitating Learning about Humans and River Systems	Curriculum material	
3	Integrating Soil Biogeochemistry into Higher Education	Curriculum material	
4	Data Visualizations	Educational movie	**Visualizing water and carbon budgets from plants to watersheds** youtu.be/N_VXC1j1cLY
5	Building Technical Capacity through CZ Workshops	Workshop materials	**Materials for CZ Time-Series Analysis Workshop: CINet and Big Data** www.hydroshare.org/resource/da6f613d405e47a39f9cc826ba7a90f9
6	Informal Professional Development for Students and Researchers	Field courses & days	**UIUC-CEE 458: Water Resources Field Methods** ws.engr.illinois.edu/custom/getsyllabus.asp?id=3430 **UIUC-GEOl 411: Geomorphology** catalog.illinois.edu/courses-of-instruction/geol
7	Sharing CZ Datasets and Communicating Findings to Research and Land Management Audiences	• RiverLab • Critical Zone	**UIUC Department of Earth Science & Environmental Change** esec.illinois.edu/riverlab **Bringing science closer to the water** las.illinois.edu/news/2022-08-26/bringing-science-closer-water **Welcome to RiverLab!** www.youtube.com/watch?v=CmE03JD3Ic0 **Meet-a-Scientist: What is the Critical Zone?** www.youtube.com/watch?v=xPLZjy-s4Hk
8	Data and Information Platform for Collaborative Watershed Planning	Web application (currently archived)	Carson et al. (2018), Xu et al. (2018); Teague et al. (2021)
9	Early Career Scientists Council	Seminar presentations	**CINet Junior Scientist Council (YouTube channel)** www.youtube.com/@cinetjuniorscientistcounci9808 **The Carbon Cycle in Agricultural and Prairie Soils of the Midwest** www.youtube.com/watch?v=wIkuOLOQp-s **Updates from RiverLab: Critical Zone Science on the Sangamon** www.youtube.com/watch?v=JhpUXFCGRNs
10	Networking with International CZ Observatories and CZ Clusters	Publications/reports	**CZ Science, Sustainability and Services in a Changing World** www.igsnrr.cas.cn/news/xshd_170746/202011/P020201102662435703490.pdf

References

Anders, A.M., Bettis, E. A., Grimley D.A., Stumpf, A. J. and Kumar P. (2018). Impacts of quaternary history on Critical Zone structure and processes: Examples and a conceptual model from the Intensively Managed Landscapes Critical Zone Observatory, Frontiers in Earth Science, Volume 6, doi.10.3389/feart.2018.00024

Anderson, S. P., Bales, R.C., and Duffy, C.J. (2008). Critical Zone Observatories: Building a network to advance interdisciplinary study of Earth surface processes. *Mineralogical Magazine,* 72(1), 7-10.

Arora, B., Kuppel, S., Wellen, C., Oswald, C., Groh, J., Payandi-Rolland, D., Stegen, J. and Coffinet, S., 2023. Building Cross-Site and Cross-Network collaborations in critical zone science. *Journal of Hydrology,* 618, p.129248.

Banwart, S.A., Chorover, J., Gaillardet, J., Sparks, D., White, T., Anderson, S., Aufdenkampe, A., Bernasconi, S., Brantley, S.L, Chadwick, O., Dietrich, W.E., Duffy, C., Goldhaber, M., Lehnert, K., Nikolaidis, N.P, and Ragnarsdottir, K.V. (2013). Sustaining Earth's Critical Zone. Basic Science and Interdisciplinary Solutions for Global Challenges, The University of Sheffield, United Kingdom, ISBN: 978-0-9576890-0-8.

Boyer, E. W. (2025). U.S. Critical Zone Collaborative Network: Selected Overview Presentations, HydroShare, [Data Resource]: http://www.hydroshare.org/resource/f815f7ea72d3417a99b7a454f223f8d3

Brantley, S. L. et al. (2007). *Frontiers in Exploration of the Critical Zone*. National Research Council.

Brantley, S. L. et al. (2017). Designing a network of Critical Zone Observatories to explore the living skin of the Earth. *Earth Surface Processes and Landforms*, 42, 1–20.

Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A. and Landes, N. (2006). The BSCS 5E instructional model: Origins, effectiveness, and applications. BSCS.

Bybee, R. W. (2015). The BSCS 5E instructional model: Creating teachable moments. National Science Teachers Association Press.

Carson, A., Windsor, M., Hill, H., Haigh, T., Wall, N., Smith, J., Olsen, R., Bathke, D., Demir, I. and Muste, M. (2018). "Serious Gaming for Participatory Planning of Multi-hazard Mitigation," The International Journal of River Basin Management, doi:10.1080/15715124.2018.1481079.

Cash, D. W., et al. (2003). Knowledge systems for sustainable development. *PNAS*, 100(14), 8086–8091.

Chein, J., et al. (2024). Visualization and systems learning in environmental decision-making. *Environmental Modelling & Software*.

CINet Jr Scientist Council (2025) Youtube Channel, https://www.youtube.com/@cinetjuniorscientistcounci9808

Frodeman, R., Klein, J. T., and Pacheco, R. C. S. (2017). *The Oxford Handbook of Interdisciplinarity*. Oxford University Press.

Goodwell, A. (2024). Materials for CZ Time-Series Analysis Workshop: CINet and Big Data, Aug 5 2024, HydroShare, http://www.hydroshare.org/resource/da6f613d405e47a39f9cc826ba7a90f9

Goodwell, A. (2025) Visualizing water and carbon budgets from plants to watersheds. Youtube, https://youtu.be/N_VXC1j1cLY, Accessed 1/8/2026

Gruenewald, D. A. (2003). The best of both worlds: A critical pedagogy of place. *Educational Researcher*, 32(4), 3–12.

Hollweg, K. S. et al. (2011). *Developing a Framework for Assessing Environmental Literacy*. NAAEE.

McCurdy, N. et al. (2016). A taxonomy of visualization for understanding dynamics. *IEEE Computer Graphics and Applications*, 36(2), 14–23.

Meadows, D. H. (2008). *Thinking in Systems: A Primer*. Chelsea Green.

Meadow, A. M. et al. (2015). Moving toward the deliberate coproduction of climate science knowledge. *Weather, Climate, and Society*, 7, 179–191.

Minor, E. S. et al. (2020). Increasing ecological literacy through place-based education. *Frontiers in Ecology and the Environment*, 18(9), 501–508.

NASEM (2018). *Graduate STEM Education for the 21st Century, Report* National Academies of Sciences, Engineering, and Medicine, National Academies Press.

National Research Council (2001). *Basic Research Opportunities in Earth Science*. National Academies Press.

Naylor, L. A. et al. (2023a). Systems approach in environmental education. *Environmental Education Research*.

Naylor, L. A. et al. (2023b). Participatory modeling for environmental decision-making. *Sustainability Science*.

New Growth Group, LLC (2025). Education & Outreach Year 5 Evaluation Report for the Thematic Cluster CINet: Critical Interface Network in Intensively Managed Landscapes Grant.

NRC (2001). Basic Research Opportunities in Earth Science, National Research Council, The National Academies Press. https://doi.org/10.17226/9981. Washington, DC.

Parrish, E. and Anderson, S. (2022). The Living Landscape: Discovering the Critical Zone. Muddy Boots Publishers, 32 pp. https://shorturl.at/Km38G

Richardson, M. and Kumar, P. (2017), Critical Zone services as environmental assessment criteria in intensively managed landscapes. Earth's Future, 5: 617-632. https://doi.org/10.1002/2016EF000517

Richter, D. D., Billings, S. A., Brantley, S.L., Gaillardet, J., Markewitz, D., Schlesinger, W. H. et al. (2024). Earth sciences are the model sciences of the Anthropocene. Perspectives of Earth and Space Scientists, 5, e2024CN000237. https://doi.org/10.1029/2024CN000237

Sermet, Y., Demir, I. and Muste, M. (2020). “A Serious Gaming Framework for Decision Support on Hydrological Hazards” Science of the Total Environment, 728, https://doi.org/10.1016/j.scitotenv.2020.138895

Singha, K., Sullivan, P. L., Billings, S. A., Walls, L., Li, L., Jarecke, K. M. et al. (2024). Expanding the spatial reach and human impacts of critical zone science. Earth's Future, 12, e2023EF003971. https://doi.org/10.1029/2023EF003971

Tague, C. and Brandt, W.T. (2023) Critical zone science in the Western US—Too much information? Front. Water 5:1226612. doi: 10.3389/frwa.2023.1226612

Teague, A., Sermet, Y., Demir, I. and Muste, M. (2021). “Serious Gaming for Water Resources Planning and Hazard Mitigation”, International Journal of Disaster Risk Reduction, 53(1), doi.org/10.1016/j.ijdrr.2020.101977
Voinov, A., Kolagani, N., McCall, M.K., Glynn, P.D., Kragt, M.E., Ostermann, F.O., Pierce, S.A. and Ramu, P. (2015). Modelling with stakeholders - next generation, Environ. Model. Software, 77, pp. 196–220.
Xu, H., Windsor, M., Muste, M. and Demir, I. (2020). A Web-Based Decision Support System for Collaborative Mitigation of Multiple Water-related Hazards using Serious Gaming, Journal of Environmental Management, 255, DOI: https://doi.org/10.1016/j.jenvman.2019.109887
White, T. S. et al. (2018). Education and workforce development in the Critical Zone. *Journal of Geoscience Education*.
Wymore, A. S. et al. (2023). Teaching systems thinking through Critical Zone science. *Earth Surface Dynamics*.