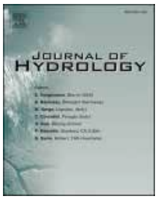
Journal of Hydrology 618 (2023) 129248

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Review papers

Building Cross-Site and Cross-Network collaborations in critical zone science

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ARTICLE INFO

Keywords:
Critical zone
Watershed
Cross-site synthesis
Data harmonization
Interdisciplinary
Available datasets

ABSTRACT

The critical zone (CZ) includes natural and anthropogenic environments, where life, energy and matter cycles combine in complex interactions in time and space. Critical zone observatories (CZOs) have been established around the world, yet their limitations in space and duration of observations, as well as the oft-existing dominant disciplinary research field(s) of each CZO may limit the transferability of the local knowledge to other settings or hinder integrative CZ understanding. In this regard, this review advocates for cross-site cross-network collaborations in CZ sciences. We posit that this type of collaboration is becoming indispensable for understanding past trends and future trajectories of the CZ, in the context of fast-developing and widespread environmental changes. Aided by a series of cyberseminars and a community survey, we highlight some of the existing cross-site initiatives, tools and techniques, and the cross-cutting science questions that could benefit from such cross-network syntheses, in various types of CZ settings (montane, alpine, arctic, managed and agricultural environments, lakes, wetlands, streams, landscapes disturbed by drought and/or wildfire, etc.). This review also identifies and discusses the major and legitimate concerns and obstacles for a collaborative CZ approach, including data harmonization and integration of social sciences, and proposes tentative ways forward.

1. Critical zone science: What? Why? Where?

1.1. What is the critical zone and what are critical zone observatories?

In 2001, a panel of the US National Research Council (NRC, 2001) put forward the critical zone concept and defined it as "a heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine availability of life sustaining resources." Simply put, the critical zone (CZ) is where most life forms have strived on Earth, and the natural habitat where our basic human needs such as water, food, and energy are sustained. In the critical zone, life, energy and matter cycles organize at a variety of scales (Chorover et al., 2007; Perdrial et al., 2015), among which the watershed (or fluvial catchment) may constitute a fundamental control volume (Rinaldo and Rodriguez-Iturbe, 2022). To apprehend the daunting complexity of these natural cycles and, crucially, how ongoing anthropogenic changes have been impacting critical zone and watershed functioning (e.g., Goddéris and Brantley, 2013), numerous long-term critical zone observatories (CZOs) and watershed sites have been established throughout the world (Brantley et al., 2017; Richter and Mobley, 2009). In the United States, the National Science Foundation (NSF) recognized the significant role that the critical zone plays in the existence of life on Earth and created the Critical Zone Observatory (CZO) program (Giardino and Houser, 2015; White et al., 2015). This was followed by the establishment of Soil Transformations in European Catchments (SoilTrEC, Banwart et al.,

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https://doi.org/10.1016/j.jhydrol.2023.129248

2011) by the consortium of European Union members. Today, there are numerous CZOs spread across the world; however, not all of these belong to a formally funded network (see Section 1.3). The term CZO, as defined here, is therefore used to describe any instrumented field site used for monitoring energy, water, and material fluxes, and biogeochemical cycles - from unaltered bedrock to the atmospheric boundary layer, across terrestrial and aquatic interfaces, and across climatic and hydrobiogeochemical gradients (Guo and Lin, 2016; Lin et al., 2011).

1.2. *Why are critical zone observatories needed?*

CZ science integrates our understanding of how water moves from the top of the canopy (e.g., trees, grass, crops) to the depths of circulating groundwater (Anderson et al., 2008; Brantley et al., 2007). CZ science also helps us quantify how long water is retained in aquifers, how much water goes to vegetation to support carbon fixation versus shunted to our streams, lakes, and reservoirs, and what controls the quality of our freshwater resources. Ultimately, it is this holistic discipline that helps us understand the mechanisms and rates at which multiple Earth surface processes and biogeochemical cycles occur, and how these may change in response to climate change, land-use practices, and changing disturbance regimes. To this end, CZ science has enabled advances in sensing and tracing technologies that have improved resolution and frequency in monitoring the hidden subsurface (Barclay et al., 2022; Mangel et al., 2022). CZ science has also fostered the growth of high-fidelity reactive transport models that test our understanding of processes (Stolze et al., 2022) and can reach beyond spatial and temporal scales of measurements (Li et al., 2017; Steefel et al., 2015). Taken together, the substantial body of CZ research provides a strong foundation for quantifying nutrient dynamics, greenhouse gas emissions, as well as water and energy exchange in the critical zone (Arora et al., 2022a; Cheng et al., 2018; Chorover et al., 2011).

It is important to acknowledge that a robust predictive understanding of how CZ and watersheds function and respond to disturbances is necessary to tackle some of the biggest challenges for the 21st century, such as water security, food and energy production, and sustainable ecosystem services. Despite significant advancements in hydrology (e.g., Hrachowitz et al., 2013; McDonnell et al. 2007), soil science (e.g., Tokunaga et al., 2019; Vereecken et al., 2016), ecology (Dawson et al., 2020), geomicrobiology (Rillig et al., 2019), biogeochemistry (e.g., Benk et al., 2019; Waterhouse et al., 2021), geology (e.g., Rempe and Dietrich, 2014; White and Brantley, 2003), climatology (Rasmussen et al., 2011) and other fields that work in the CZ, accurately predicting CZ functioning requires study of the interactions among dominant processes across landscapes. Given this complexity, recent studies have highlighted the need for more holistic, integrative and multiscale approaches that work at the intersections of traditionally separate disciplines to advance our understanding of CZ functioning. For example, Saup et al. (2019) demonstrated the tight linkage between microbial community assembly and seasonal hydrology in the Upper Colorado River Basin. They make the point that understanding hydrological drivers of microbial activity is important for systems whose flow regime may be impacted under future climate scenarios. Similarly, Li et al. (2021) advocate for developing integrated theories at the intersection of hydrology (e.g., transit time theory) and biogeochemistry (e.g., reaction kinetic theories), which they argue are at the core of CZ functioning and necessary to improve our understanding of, and ability to predict, earth surface system responses to climate and human forcing. These calls for more integrated CZ research will require interdisciplinary knowledge exchange and adaptation of concepts beyond discipline-specific boundaries (Adler et al., 2021; Arora et al., 2022b; Brantley et al., 2017; Perdrial et al., 2015).

Advancing our understanding of CZ functioning at relevant local and global scales also requires addressing the tremendous spatial variability in dominant processes across natural and human-impacted landscapes (Elhacham et al., 2020; Ellis et al., 2021; Grant et al., 2017). The importance of addressing scaling effects in CZ science is easily illustrated when considering the cascading impacts of changes in climate and land cover/use on water quality in large watersheds. For example, the Mississippi River starts as a humble 6 m wide knee-deep creek in north-central Minnesota. As it flows southward, it picks up excessive nutrients from the agricultural and urban landscapes in the center of the continental United States, before discharging into the Gulf of Mexico and creating an expansive “dead zone” of 16,405 km^2 (NOAA, 2021). Another example is the Yellow River, a major drinking water source in China and the second-longest in Asia, that has been suffering from extensive contamination and is now on the verge of becoming unfit for even industrial or agricultural use (Dwivedi et al., 2022a). Existing CZOs do not operate at these scales, so it is important to consider the representativeness of individual CZ sites for larger systems and consider opportunities for cross-site synthesis to grasp the impact of spatial variability on downstream conditions.

Further, while the scale and complexity of these water quality impacts is daunting, large investments have already been made in developing these CZO sites, which constitute collecting phenomenally diverse and distributed watershed datasets, including many associated with autonomous sensing systems. It is worthwhile to acknowledge that comparable measurements exist at CZOs at national and international scales. Together, these datasets share many common attributes, but differ by important aspects such as geophysical attributes, climatic conditions, plant functional types, biodiversity, inherent complexity (e.g., natural/built environment), disturbance types (e.g., fire, heat wave, flooding, mining) and time since disturbance (e.g., logging, insect infestation). An international network of watersheds and CZOs can serve as a vehicle for knowledge exchange, integration, and scientific discovery. Strengths of such a network include its ability to detect emergent scale properties of watershed and CZ function at local to regional and global scales, and provide an in-depth understanding of the spatially heterogeneous impact of disturbances on watershed function.

1.3. *Where are critical zone observatories located?*

As suggested above, these CZOs are located worldwide (Fig. 1). However, these individual sites have traditionally operated in silos with frequent emphasis on their specific design, regional setting, and priority science questions that have resulted in customized data collection, theories and modeling approaches (Arora et al., 2021; Brantley et al., 2021; Lesmes et al., 2020). While there is a wide diversity of sites (Fig. 1), a common challenge across these sites is to understand and predict how sustainable or vulnerable these habitats and associated services are in the face of compounding and co-occurring climatic disturbances and rapidly growing population, industrialization and urbanization.

Many of these CZOs belong to a larger network (e.g., DOE Watersheds, CZCN, OZCAR, TERENO) that were designed with specific strategic goals; however, there are many sites (including those not listed on this map) that are well established (e.g., long-term, interdisciplinary, indigenous community-led) but not formally part of a funded network and therefore lacking in aspects that promote data sharing/cross-site comparisons. There is room to advocate for both individual and larger-scale CZO network development and network-of-networks. For example, there is significant underrepresentation of the intertropical belt among the established CZOs (Fig. 1), although this latitudinal range harbors over half of the world population, two-thirds of the terrestrial plant biomass (Chapin et al., 2002), and may face some of the most dramatic impacts of ongoing global changes (Mamalakis et al., 2021). Connecting individual sites in a network-of-networks fashion in the inter-tropical belt is likely to be impactful in transforming our understanding of CZ functioning in these regions.

Based on this assessment, we first present an overview of where the lack of a network-of-networks organization comes at a substantial cost to the CZ community through missed opportunities to address scientific

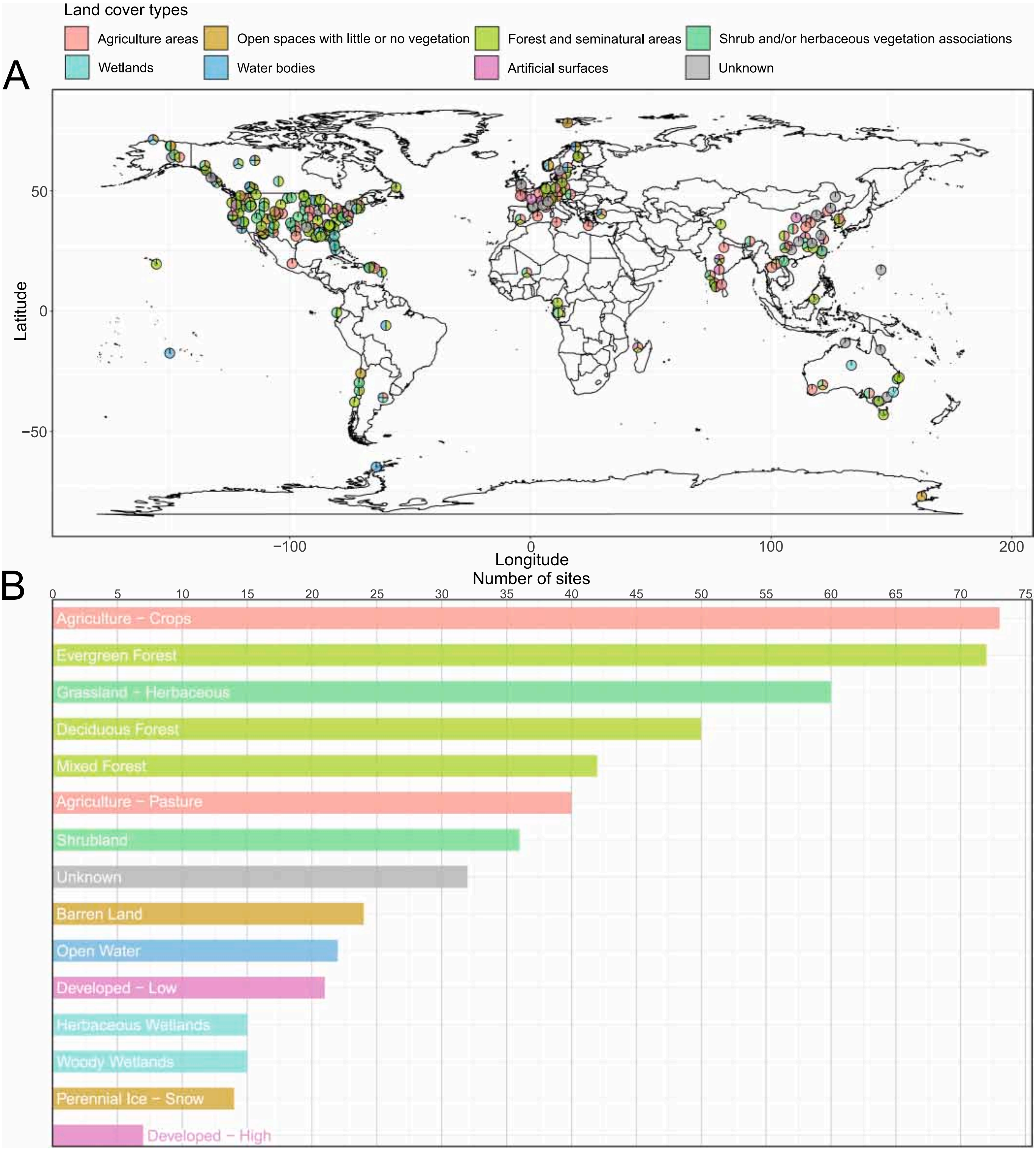

Fig. 1. World map of networked and independent Critical Zone Observatories and long-term research catchments (A) and overview of land cover type per site (B) as of June 2022. Please note that the land coverage is not evenly distributed. (source: https://www.czen.org/site_seeker, last access 12 September 2022, and several sites in Canada by personal communication with individual site investigators).

challenges (Section 2). We then describe existing cross-site cross-network initiatives and where these initiatives are urgently needed (Section 3). In the same spirit, we list available and emerging synthesis, tools and techniques that provide a springboard for new modes of collaboration (Section 4). We then summarize the challenges within the context of implementing a network-of-networks model (Section 5). In the same section, we also highlight community debates regarding the need to integrate human and social perspectives in CZ science (Section 5.2). We identify-three areas of greatest need in order to achieve higher rates of data sharing and reuse under a network-of-networks framework: open and standardized metadata guidelines, data harmonization, and a new class of CZ information scientists (Section 6.1). We suggest specific guidance for addressing these needs and describe the principles for enhancing cross-site and cross-network collaborations in the CZ (Section 6.2). The proposed network-of-networks model is expected to promote synthesis/integration activities across CZ networks, develop transferable tools, data and workflows, train next generation of CZ scientists, open new sources of funding, build personal connections and human-to-human interaction, as well as engage CZ site managers and relevant stakeholders. The network-of-networks setup is presented as a framework for improving how human management decisions and adaptation strategies impact CZ functioning at a global scale, informing policy development and enabling socio-ecological innovations (Section 6.2). The paper concludes with a recommendation to develop an open, inclusive, international network-of-networks framework that promotes the use of the "best available" science to address the most pressing challenges of the CZ (Section 7).

2. The need for a radical collaboration across CZOs

The CZO concept has been successful in integrating across diverse and distributed measurements for the purposes of understanding the complex and tightly coupled interactions of hydrological, biogeochemical, geological, microbiological, and ecological processes at an intensively-monitored site (Anderson et al., 2008; Kulmala, 2018). However, CZOs require massive investment and coordination between dozens of scientists to gain this in-depth understanding (Guo and Lin, 2016). Moreover, the technologies needed to observe key ecosystem fluxes directly, including evapotranspiration and greenhouse gas fluxes (e.g., FLUXNET, Pastorello et al., 2020) and indirectly such as biogeochemical transformations and nutrient uptake (e.g., NutNet, Adler et al., 2011), often need to be observed at very fine spatial scales (e.g. 0.01 km^2, Baldocchi et al., 2001) or in-situ (Morin et al., 2017; Petrescu et al., 2015). As such, the knowledge obtained from CZOs is challenging to apply directly to the large areas we seek to manage and/or protect, for example the Mississippi Basin or the Yellow River.

Beyond the spatial context that is critical for underpinning resource management decisions, co-occurring and compounding disturbances are testing the resilience of CZ and watersheds in new and poorly understood ways. Natural and anthropogenic forms of disturbance are pushing these systems to tipping points beyond which many previously stationary environmental rates – including rates of erosion and sediment control, groundwater recharge, contaminant mitigation and associated microbial and ecological processing (among others) - are rapidly changing (e.g., McDowell et al., 2008; Newcomer et al., 2021; Wohl, 2013). This has had devastating effects on biodiversity and ecosystem services in the CZ (Díaz et al., 2019). Co-occurring disturbances, such as water and resource extraction combined with widespread drought are leaving little for ecological communities, while compound disturbances are exacerbating soil fertility and water quality issues. Recent reports from the Intergovernmental Panel on Climate Change (IPCC, 2021) stress a clear urgency to understand how natural systems, including CZ and watersheds, will respond to disturbance. Models predict that the global water cycle will intensify under a warming climate where for each 1 °C rise in temperature, global precipitation is projected to increase approximately 1 – 3 % (IPCC, 2013; Roque-Malo and Kumar, 2017); however, this increase is not expected to be uniform across latitudes or seasons (Xie et al., 2015).

By integrating information from several CZOs, we can answer questions about how multiple processes are coupled, how they vary across broad gradients, and how they respond to disturbance (e.g., Gaillardet et al., 2018). For instance, a large river basin like the Mississippi basin is typically studied through CZOs that occupy a tiny proportion of its area. Through traditional modes of inquiry, this implies that the community has assembled a substantial body of observations and process-specific interpretations that are relevant to the intensely monitored CZO site(s). However, we are still lacking a unified conceptual framework that can translate this knowledge into transferable and generalizable concepts. But, working across CZO networks, for example, in France and Germany in addition to the Mississippi basin CZOs, could yield a detailed understanding of how diverse environments function and respond to future disturbances. At the very least, such an approach would enable unifying data, theories and models across CZOs and disturbance events with the capacity to test hypotheses across a larger parameter space than would be possible within any single CZO. It is precisely this rationale that underpins the development of CZO networks, and its logical extension is that coordination across networks is needed as greater scales are to be assessed. Considering the presence of pre-existing networks of CZOs usually maintained by a particular national government and focused largely within its territory, it follows that a continental to global focus of inquiry requires some degree of working across these already-established networks. The Global Ecosystem Research Infrastructure (GERI, Loescher et al., 2022), which collaborates with five major ecosystem research infrastructures around the globe (NEON/North America, eLTER/Europe, ICOS/Europe, TERN/Australia, CERN/Asia, and SAEON/Africa) is a good example of an established network-of-networks. Further, there have been calls for an integrated earth observatory (e.g., Kulmala, 2018) as the best means to address global problems such as climate change. However, it is important to recognize that such an effort requires detailed ground data including, but not limited to, soil properties, nutrient stocks and transformations, carbon pools and transformations, and microbial functioning, to constrain processes such as greenhouse gas fluxes, nutrient transformations, and hydrological processes (Arora et al., 2016; Vicca et al., 2018; Jansson and Hofmockel, 2020) as well as assessing the response to disturbance (Graham et al., 2021; Grant et al., 2019). Providing such data will require a global coordinated effort and is likely to require working across networks of CZOs.

Integrating and collaborating across these observatories and networks also becomes increasingly indispensable for understanding how CZ might behave under conditions substantially different from the present ones. For example, in a microbial context, an outstanding science question is to understand to what degree the response of a microbial community to a disturbance is ecosystem-limited, and can the response be generalized as a functional trait that could then be used to make predictions and management decisions regarding future events. If microbial datasets are collected in standardized ways across the global CZ, these data types can be used to reveal generalizable patterns, rules, concepts, and theories tied to a broad range of microbial properties related to ecology (e.g., large-scale diversity gradients), evolution (e.g., processes governing strain variation), and function (e.g., microbial food webs structured by metabolite exchange). Taking a coordinated approach spanning CZOs will dramatically accelerate the pursuit of generalizable or transferable knowledge, which is essential to develop predictive models (e.g., Earth system models) that are ultimately tied to developing solutions to sustainably manage ecosystems following disturbance. More generally, working across networks of CZOs can help test the generality of concepts and hypotheses (e.g., Jansson and Hofmockel, 2020) and generate new hypotheses for further evaluation *via* modeling and targeted data generation.

3. Opportunities to conduct cross-site cross-network science

3.1. Examples of existing cross-site initiatives

Although limited in number, recent studies that are targeting data from multiple international sites are far-reaching and already creating paradigm shifts in our understanding of watershed and CZ functioning (e.g., Tiegs et al., 2019; Migliavacca et al., 2021). As an example, a global analysis of intermittent rivers and ephemeral streams spanning more than 200 dry riverbeds across major environmental gradients and climate zones is providing important insights on terrestrial plant litter dynamics (Datry et al., 2018). Another example is a global low-cost analysis using household tea bags – known as the TeaComposition

Initiative - to elucidate microbial carbon cycling across ecosystems and climatic regions (Djukic et al., 2021). There are also significant emerging efforts focused on collecting extensive observations of hydroclimatic, microbial and hydrologic variables across diverse environments (e.g., CHOSEN, WHONDRS) (Zhang et al., 2021; Stegen and Goldman, 2018). A recent study by Ward et al. (2022) further demonstrates the power of prodding such extensive datasets using machine learning approaches. Focused on river corridor science, their study uncovered relationships that would not have been possible through traditional, deductive approaches to science. However, we must recognize that cross-site initiatives and data gathering efforts that cover a large spatial domain, but do not provide a holistic, interdisciplinary view of CZ processes may not be enough to advance CZ science. For instance, the NSF has taken a step to address this challenge by reorganizing their CZO program to develop 10 new Critical Zone Collaborative Networks (CZCNs) that all but one focus on science/hypothesis driven research across multiple, national CZ sites. The last CZCN funding supports the development of a network coordinating hub. Although limited to the national scale, these multi-site investigations and hub are expected to not only improve our understanding of CZ dynamics, but also provide a platform to facilitate exchange of data, information and learning opportunities for CZ scientists and students alike. With this in mind, outcomes from globally-distributed efforts like intermittent rivers, CHOSEN, WHONDRS and the TeaComposition Initiative as well as NSF-led national efforts can be powerful catalysts for further cross-network integration and coordination.

3.2. Opportunities for new cross-network synthesis identified through CZ community discussions

Below, we highlight some increasingly urgent science questions that could benefit from cross-site and cross-network collaborations. These are assembled from a recent cyberseminar series (CUAHSI, 2021a) showcasing CZOs across bioclimatic settings, key science questions being addressed at each CZO, and perceptual models developed at each site that could be tested across a diversity of CZO sites to improve process understanding (Table 1). These encompass montane, alpine and arctic, managed and agricultural, drought and wildfire impacted, as well as lake, wetland and stream environments. As would be obvious, there are opportunities for improved understanding of CZ processes in landscapes not described here or discussed during the cyberseminar series. To expand on this further, the next section (section 3.3) describes these outstanding opportunities with an acute focus on urban landscapes.

3.3. Other examples of outstanding CZ-related challenges

Although not explicitly discussed during the 2021 CUAHSI cyberseminar series (or described in Table 1), there are opportunities for improved understanding of CZ processes in other landscapes undergoing rapid and drastic change, for example tropical forested landscapes, urban areas (especially those along coastlines), intermittent river and variably inundated settings. Below, we take the example of urban landscapes to illustrate how we could benefit from a concerted effort to generate and test hypotheses through synthesizing and analyzing information across a variety of sites and networks.

As shown in Fig. 1, urban landscapes can be classified as ‘Developed - High’ land cover according to National Land Cover Database (Dewitz and U.S. Geological Survey, 2021), which includes 4 sites (Eel River CZO, Central Arizona - Phoenix LTER, Baltimore Ecosystem Study, and Plum Island Ecosystem LTER) and as ‘Developed - Low’ that includes 17 additional sites. More recently, the NSF CZCN funding was awarded to develop an urban CZ cluster spanning four cities in the U.S. East Coast (Philadelphia, Baltimore, Washington D.C., and Raleigh) (Weniger et al., 2021). The north–south gradient these sites fall along captures climatic trends and urban development trends (i.e., older and denser development in Philadelphia and Baltimore to newer and sparser development

Table 1
Examples of science questions and perceptual models that can be tested across similar CZO settings as identified by CUAHSI cyberseminar participants (CUAHSI, 2021a).

Type of CZO setting	Cross-cutting science questions	Perceptual models
Montane environments	How does water partition along steep mountainous gradients as a function of snow dynamics and watershed characteristics?	Catchments with faster drainage rates are generally less sensitive to changes in precipitation inputs.
	What is a dominant control on CZ thickness?	Vegetation plays an important (if not dominant) role in transforming bedrock to regolith.
	What impact does water table fluctuations have on exports and river chemistry?	Spatially-variable exports in response to water table fluctuations can be aggregated into an integrated watershed concentration-discharge (C-Q) signature.
	How does deep bedrock weathering govern elemental exports?	Plant-microbe-mineral interactions act together to alter water and solute exports from deep bedrock.
	Do sediment fluxes in mountainous areas show increasing trends under climate change?	The relationship between mountainous sediment yield and precipitation is opposite to the Langbein-Schumm curve.
Alpine and Arctic environments	Is the Arctic becoming wetter or drier due to environmental changes?	Thermokarst and preferential flow occurrence is increasing in Arctic environments.
	How to foster awareness (education, communities) about environmental issues and ongoing/future disturbances based on the richness of observatory-based research across networks?	Cross-network permafrost research is necessary to assess the magnitude and persistence of responses, for example climate feedback.
	Warming brings increasingly synchronized greening and flowering across a range of elevation. Is there a threshold due to, for example, cooler temperatures at more extreme elevations?	Photosynthesis (GPP) sensitivity to CO_2 elevation depends on ecosystem altitude.
	There is a trend towards earlier spring snowmelt, but delayed spring snowmelt runoff is being increasingly observed; why?	At a minimum, the net impact of climate and permafrost changes will be determined primarily by hydrological connectivity.
Managed and agricultural environments	In dry sedimentary and agro-expanding regions, what are the most relevant groundwater-mediated mechanisms dictating the outcome of plant water uptake (evapotranspiration) versus stream runoff “competition”?	While plants can use unsaturated, riparian and saturated water stores to fulfill their demand, deepening stream incisions in dry sedimentary and agro-expanding regions can lower groundwater accessible to plants.
	In carbonate-dominated dryland CZ sites, what factors control CO_2 efflux under natural versus irrigated systems?	The major controlling factors on CO_2 efflux in irrigated systems with pedogenic carbonates are soil substrates, climatic conditions (evaporation to push the saturation rates), irrigation style (water chemistry and intensity) and the competition

(*continued on next page*)

Table 1 (*continued*)

Type of CZO setting	Cross-cutting science questions	Perceptual models
		between dissolution and precipitation reactions.
	What impact does groundwater pumping have on streamflow?	In tropical hardrock aquifers, intense and/or sustained groundwater pumping for irrigation may create an inverse groundwater level gradient as compared to topography, create spatially and temporally intermittent groundwater connectivity, disconnect streams and groundwater, and eventually dry out streams.
Landscapes disturbed by drought and/or wildfire	Do climate induced changes in landscape characteristics and hydrology (e.g., permafrost thaw and transition to forest cover) change an environment's vulnerability to drought and wildfire?	Heavily managed landscapes (e.g., forest monocultures, landscape drainage for agriculture, urban) are not as resilient to drought and/or wildfire as natural landscapes.
	What is the relationship between surface water-groundwater interactions and drought vulnerability in semi-arid and/or seasonally frozen environments?	Drought clearly impacts the water cycle across varied landscapes, but wildfire disturbance does not necessarily result in significant change in dominant hydrological processes. Disturbance can induce changes in biogeochemical characteristics/functioning of streams.
	How do repeated wildfire events impact the hydrological, biogeochemical and microbial conditions of a river and its watershed?	The concentration of some solutes (e.g., nitrate) in the stream increases as the area of burn increases. However, not all water quality parameters respond in the same manner, suggesting that watersheds can have significant buffering/resilience capacity to fire disturbance.
	Does anthropogenic land use change in deep loess landforms (e.g., transition from cropland to orchards) change the landscapes vulnerability to drought?	Anthropogenic land use change in deep loess landscapes can lead to soil degradation, vegetation die-off, afforestation failure, soil drought, and changes in the C and N accumulation in soils.
	What are the long term effects of sustained multi-year drought on forest ecosystem functions and susceptibility to pests?	Drought and extreme storms can exacerbate insect infestations in forested environments.
Lakes, wetlands and streams	What drives biogeochemical and geomorphological changes in coastal ecosystems?	Marshes migrate inland due to coastal changes (e.g., sea level rise and flooding), resulting in drastic changes to prevailing ecosystems (e.g. forests).
	Is global warming causing a deterioration of water quality of lakes?	Climate change affects the ecosystem of lakes through changes in water temperatures and mixing and stratification behavior, and thus oxygen and matter exchange, which leads to algal blooms.
	How do fresh and marine hydrologic pulses interact with other long-term changes and disturbances to influence ecosystem trajectories?	The deposition of phosphorus rich sediments by marine pulses (i.e. hurricanes) has a positive effect on the mangrove ecosystems (fertilization effect and elevation gain).

in Raleigh). This urban CZ cluster is focused on addressing the drivers of solute export dynamics in urban areas, including the potential importance of climate, urban density, underlying geology, and the unique hydrological functioning of urban landscapes. The OZCAR network in France also has several urban impacted sites, including Fontaine de Vaucluse near Nîmes, the OTHU Yzeron site near Lyon, and the OSUNA-IRSTV-ONEVU site near Nantes. Urban research catchment sites that are not part of an existing CZ network also exist, for example, the Black Creek Research Catchment in Toronto, Canada and a number of urban-impacted catchments across Berlin, Germany (Kuhlemann et al., 2020; Kuhlemann et al., 2022), which have both been used to deepen our understanding of water ages and their relationship to solute transport in urban streams.

Across these sites, many unanswered research questions related to the impacts of urban development on CZ processes have emerged. For example, the role of pervious areas (e.g., lawns, parks, brownfields, riparian areas) in the transport of water and solutes to receiving waters (Ariano and Oswald, 2022), as well as, spatial and temporal variability in greenhouse gas fluxes, is starting to receive more attention. Notable in urban pervious areas is the heterogeneity of urban soils due to human disturbance (e.g., construction activities, compaction). The influence of these patterns on pollutant sources and transport, and the success of urban vegetation deserves additional attention. There is also an emerging interest in quantifying the ecohydrological partitioning of precipitation into 'blue fluxes' and 'green fluxes' in urban greenspaces (Gillefalk et al., 2022; Marx et al., 2022) and the role of different vegetation species, which are usually heavily managed, on these fluxes. Investigations into the dominant biogeochemical processes facilitating the mobilization of contaminants of emerging concern (e.g., plastics, plastic-associated contaminants, pharmaceuticals), which are often concentrated in areas with high population density, are also increasing (Kaushal et al., 2020; Fork et al., 2021; Werbowski et al., 2021). The role of wastewater as a pathway for contaminants of emerging concern to enter surface waters, and the impacts of wastewater contributions on stream biogeochemical processing in general, are of interest.

While many of these lines of inquiry could be investigated within a single CZO or research catchment, there are clear benefits to addressing these questions across networks and urban CZ sites. There are fundamental differences in the materials and plans of cities, including the types of infrastructure in place and management practices, which may have an outsized impact on the importance of these processes. For example, older cities may have more degraded sewer infrastructure, which could lead to more wastewater inputs to surface water systems. Although we could examine how urban CZ processes are impacted across climatic gradients in a manner similar to any cross-site, cross-network study; here, we have the opportunity to prioritize examining gradients of urbanization (e.g., there may be different processes occurring in areas with low levels of urban land cover versus heavily urbanized areas). Since urban CZ science has not been a traditional priority (i.e., it is atypical to have as many urban sites in one country as the U.S. or France), leveraging measurements across multiple sites is advantageous for inferring process from pattern.

Other outstanding, overarching CZ research questions include: How do different CZ/watershed sites respond to similar compound and co-occurring disturbances? What determines differences in site responses to similar disturbances? How does environmental history modulate these responses? To what extent are model/machine learning parameters transferable to untested sites and unforeseen conditions? What tools exist to make the data more accessible and open for cross-site cross-network comparisons?

4. Available and emerging synthesis, tools and techniques

In this section, we focus on highlighting available and emerging tools and techniques for cross-site, cross-network science that were identified by seminar participants in a second CUAHSI cyberseminar series (CUAHSI, 2021b).

4.1. Existing and emerging frameworks and platforms for successful data synthesis

As suggested above, there now exist a few, albeit limited, studies targeting global standardized experiments and developing flexible tools with data from multiple international sites. Crucial enablers of such synthesis activities are existing and emerging interoperable portals for browsing, sharing, publishing, and analyzing CZ data. These include the CUAHSI HydroClient (https://data.cuahsi.org) and HydroShare (https://hydroshare.org) portals, the global scale OZCAR-Theia data portal (Braud et al., 2020, https://in-situ.theia-land.fr/), the TERENO data discovery portal (https://ddp.tereno.net/ddp/), the Department of Energy’s ESS-DIVE portal on watershed and instrumented sites (https://ess-dive.lbl.gov/), or the Macrosheds portal for US stream and watershed data (https://cuahsi.shinyapps.io/macrosheds/). The latter also includes tools for training models with hosted datasets. Another example is the Datastream portal hosted by the Gordon Foundation (https://gordonfoundation.ca/initiatives/datastream/), which makes it easy to share and access water quality data. A more extensive listing of existing regional and international data portals is provided in Table 2. We recognize that the highly distributed nature of CZ data repositories - as is evident from Table 2 - can require substantial efforts in ensuring data access and discovery. In section 6.1.1., we make recommendations on how to make these data easily and automatically accessible and discoverable through a global catalog of CZ data stores across networks. However, efforts to institute a data collection or storage standard will likely have the effect of stifling innovation in CZ science, while also becoming unwieldy. Rather than standardize data collection or storage, we argue for the development of shared metadata template(s). These must be developed as a community effort and would enable more efficient but flexible data storage, collection, and discovery (see section 6.1.1 for further details).

Online infrastructures integrating models and data analyses are emerging as well, from large platforms such as the IDEAS-Watersheds Software Ecosystem, https://ideas-productivity.org/ideas-watersheds/) which comprises workflow tools, interface libraries and a variety of codes for reactive transport, hydrological or land surface modeling, all the way to specific toolboxes such as BridgET (https://github.com/KIT-HYD/bridget) for comparing and scaling evapotranspiration estimates.

Beyond existing portals, synthesis activities have been focused on curating specific CZ data from a variety of sites. Successful examples of such activities include the Soil Water Infiltration Global (SWIG) database, which includes more than 5000 infiltration curves covering all continents with an acute focus on developing, evaluating and validating infiltration processes across a range of models (Rahmati et al., 2018). In the United States, the CHOSEN (Comprehensive Hydrologic Observatory Sensor Network) is a database of streamflow, soil moisture, and other hydroclimatic and hydrologic variables, a comparative analysis of which highlighted complex patterns in hydrological extremes across different

Table 2
Examples of large datasets or data portals related to the CZ, grouped into categories of observables; from multidisciplinary to discipline- or compartment-specific instances.

Network	Region	Type	Link & Reference
HydroClient	Worldwide	Multidisciplinary	CUAHSI HydroClient https://data.cuahsi.org/
LTER	Worldwide	Multidisciplinary	Gries et al., 2019 https://edirepository.org/
NEON	US	Multidisciplinary	Metzger et al., 2019 https://www.neonscience.org/data
DOE Data Explorer	US	Multidisciplinary	https://www.osti.gov/dataexplorer/
INTERACT	Arctic	Multidisciplinary	Topp-Jørgensen et al., 2015 https://eu-interact.org/
OZCAR	France / Worldwide	Multidisciplinary	Gaillardet et al., 2018 https://www.ozcar-ri.org/
TERENO	Germany	Multidisciplinary	Zacharias et al., 2011 https://www.tereno.net/
POLAR Data Catalogue	Arctic / Antarctic	Multidisciplinary	Friddell et al., 2014 https://www.polardata.ca/pdcsearch/
CAMELS-US	US	Hydrometeorology, catchment attributes	Addor et al., 2017 https://ral.ucar.edu/solutions/products/camels
CAMELS-GB	UK	Hydrometeorology, landscape attributes	Coxon et al., 2020 10.5285/8344e4f3-d2ea-44f5-8afa-86d2987543a9
CANOPEX	Canada	Hydrometeorology	Arsenault et al., 2016 http://canopex.etsmtl.net/
GNIP	Worldwide	Precipitation isotopes	International Atomic Energy Agency, 1992 https://www.iaea.org/services/networks/gnip
SMHI	Sweden	Meteorology	Omstedt et al., 1997 https://www.smhi.se/data/utforskaren-oppna-data/
FLUXNET	Worldwide	Surface-atmosphere fluxes of carbon, water and energy	Pastorello et al., 2020 https://fluxnet.org/data/
LIAISE	Spain	Land surface interactions	Boone et al., 2019 https://liaise.aeris-data.fr/products/
SoDaH	Worldwide	Soil organic matter	Wieder et al., 2021 https://lter.github.

(continued on next page)

Table 2 (*continued*)

Network	Region	Type	Link & Reference
ESDAC	Europe	Soils	io/som-website/index.html Panagos et al., 2012
Bonares	Europe	Soils and agrosystems	https://esdac.jrc.ec.europa.eu/ Svoboda and Heinrich, 2017
ISMN	Worldwide	Soil moisture	https://www.bonares.de Dorigo et al., 2021
COSMOS-Europe	Europe	Soil moisture (cosmic-ray neutron sensors)	https://ismn.geo.tuwien.ac.at/en/ Bogena et al., 2022
National Soil Moisture Network	US	Soil moisture	10.34731/x9s3-kr48 Quiring et al., 2016
DataStream	Canada	Hydrology	https://nationalsoilmoisture.com/ https://gordonfoundation.ca/initiatives/datastream/
HYDROSHARE	US	Hydrology	Horsburgh et al., 2016
LamaH-CE	Central Europe	Hydrology, environmental science	https://www.hydroshare.org/ Klingler et al., 2021
Macrosheds	US	Hydrobiogeochemistry	https://zenodo.org/record/5153305 Vlah et al., 2022
CHOSEN	US	Hydrology	https://cuahsi.shinyapps.io/macrosheds/ Zhang et al., 2021
CAMELS-Chem	US	Hydrobiogeochemistry	https://zenodo.org/record/4060384 Sterle et al., 2022
WHONDRS	Worldwide	Hydrobiogeochemistry	https://drive.google.com/drive/folders/1AF37U3jXW8nxIe195bb2nN2HDpDsdKVr Stegen and Goldman, 2018
GNIR	Worldwide	Stream water isotopes	https://ess-dive.lbl.gov/ International Atomic Energy Agency, 2012
National dataset of streamflow isotopes	Canada	Stream water isotopes	https://www.iaea.org/services/networks/gnir Gibson et al. 2021 Data link

US regions thereby advocating for long-term observatories (Zhang et al., 2021). Other efforts focused on global datasets of high-dimensional, high-resolution microbial properties and processes across diverse CZ environments are also emerging. In this regard, the Worldwide Hydrobiogeochemistry Observation Network for Dynamic River Systems (WHONDRS) has been carrying out crowdsourced sampling campaigns that span numerous networks and countries, though significant global gaps remain (Stegen and Goldman, 2018). In this campaign, the microbial data - once fully available - can provide a foundation to elucidate organizing principles governing spatial and temporal patterns in microbial composition (e.g., which microbes are where) and function (e.g., what genes are expressed before/after disturbance). These microbe-oriented questions are particularly important in the CZ and Earth System functioning at large, as microbes are primary catalysts for organic matter transformations tied to greenhouse gas production and global biogeochemical cycles. Such data collection and integration efforts are important for bridging scales as they can provide standardized and transferable insights across the globe.

4.2. State-of-the-art tools and techniques for reducing complexity

Beyond data integration portals and frameworks, conducting synthesis crucially relies on translating complex CZ information into a compelling scientific narrative. One approach to reducing complexity in studied systems -even more so across a large array of observation sites- is to use dimensionless numbers. This is because dimensionless numbers have the potential to collapse the scatter in data, highlight scale invariance, express the competition between processes, and allow for comparing datasets, model outputs, and/or locations with different characteristic ranges. Classical examples include the Reynolds number in fluid dynamics (Abraham, 1970), the combination of the dryness and evaporative indices (both dimensionless) in the Budyko curve in hydroclimatology (e.g., Berghuijs et al., 2014), the Damkhöler number in reactive transport, or the Hillslope number in hydrology (e.g., Brutsaert, 1994; Berne et al., 2005). A related approach to reducing complexity in studied systems relies on a mix of hydrological (or biogeochemical/ecological/climatic) signatures. For instance, Braud et al. (2021) used a number of hydrological signatures such as baseflow index, flow duration curve slope, and event recession curve indices, together with a cluster analysis, to classify OZCAR sites across four continents. Their approach was quite scalable and would be straightforward to apply to even larger networks of data, and has the potential to allow fairly broad classifications of catchments based on function. In a separate cross-site study, Ross et al. (2021) used the idea of hydrological thresholds of intensity and storage to analyze 21 catchments across the US, Canada, Australia, and New Zealand. In particular, they identified thresholds in runoff response at all but one catchment, and concluded that threshold behavior can be one basis of studying a large number of catchments.

Another approach builds on the idea of using stream properties (e.g., solutes concentrations) as a proxy for upstream CZ structure and processes, with the most widely-used approach being the concentration-discharge (C-Q) relationship where river discharge rate (Q) reflects different CZ compartments mobilized (e.g., Gaillardet et al., 1999; Stewart et al., 2022). Rather than absolute solute concentration or river discharge, one can use the relationship between the two, or with dimensionless numbers such as concentration ratios, or even their derivatives (differential C-Q analysis, Arora et al., 2020), to collapse data scattering and reflect CZ functioning, but more importantly to facilitate synthesis and hypothesis testing across diverse observatories. Some of these non-exclusive approaches can further track the transient nature of underlying CZ processes, both in time ("hot moments") and space ("hot spots") within the studied landscape and time periods, using dedicated methods such as wavelets and wavelet-entropy analysis (e.g., Arora et al., 2019; Grande et al., 2022). Cross-CZ synthesis efforts may also benefit from overcoming "small scale paradigms", as only very few out of various candidate CZ processes may actually play a role at larger scales or explain inter-site variability (e.g., Adler et al., 2021). Data analysis methods aimed at dimensionality reduction (e.g., principal component analysis, isometric feature mapping) can be a path forward to identifying these key drivers or processes (e.g., Schilli et al, 2010 on soil solution characterization, or Wlostowski et al., 2021 on hydrological signatures). These data analysis techniques have been increasingly combined with, or paralleled by, machine learning (ML) techniques (e.

g., Zhi et al., 2021), which allow for CZ drivers and patterns to be identified with minimal *a priori* knowledge. If sufficient data points are available, ML is often considered to be more flexible than other approaches as it does not need all data to be rigidly collected with the same frame (Dwivedi et al., 2022b; Varadharajan et al., 2022). Its application in CZ science is still in its infancy, notably due to significant challenges such as the interpretability and physical consistency of ML models, the need to include complexity and uncertainty of training data in ML models, and the enormous computational resources needed in many ML applications (Reichstein et al., 2019; Sahu et al., 2020; Burdett and Wellen, 2022). For example, Burdett and Wellen (2022) found that while ML approaches outperformed more conventional statistical techniques in the prediction of crop yield from soil properties, an attempt to quantify the most important factors for prediction revealed substantial uncertainty. While the two predictors with the highest level of variable importance in a random forest model alone were able to achieve very strong fits to the crop yield data, a model nearly as strong was assembled from the three variables of lowest importance. However, ML is a fast-growing field of research and some of these challenges are already being addressed. For instance, hybrid methods are increasingly being applied, such as differential parameter learning where the training focuses on calibrating the parameters of a process-based model efficiently yielding spatially and physically coherent parameter configurations for distributed simulations (Tsai et al., 2021).

The need for synthesis studies and cross-site CZ analyses have also promoted the search for reliable proxies where data gaps exist. For instance, electrical conductivity (EC) is often used as a proxy for chloride concentrations in urban systems, allowing a continuous record to be reliably derived from a relatively small number of grab samples (Moore et al., 2019). The mechanisms for why EC influences chloride so consistently are well established - at very high Cl concentrations, the Cl contributed from road deicers is the main source of ionic strength (Cooper et al., 2014). Other proxies for chemical constituents have a much less consistently reliable relation with important variables. For instance, FDOM (fluorescent dissolved organic matter) sensors allow dissolved organic carbon (DOC) to be monitored, but often corrections are required to account for turbidity, temperature, and other important variables (Downing et al., 2012). Turbidity sensors often have strong relationships with total suspended solids and total phosphorus, and often reasonable relationships with dissolved phosphorus, but the strength of these relationships varies substantially, even in areas with similar climate and geology (e.g., Biagi et al., 2022; Robertson et al., 2018; Ross et al., 2022). Presumably the details of the erosional processes and also the biogeochemistry dictate this relationship. A widespread network effort could provide a mechanistic understanding of why certain sensors are reliable proxies for water quality parameters in some catchments but not others, and could help manage expectations of sensors (e.g., Rode et al., 2016). A host of other sensors are used to monitor various CZ processes, e.g. soil moisture, snowfall, precipitation, vegetation cover (Phenocam, Sonnentag et al., 2012), water quality, and others. Previous intercomparison studies have reported significant variability across sensors when different sensors are sensing the same variable in the same place (e.g., soil moisture, Jackisch et al., 2020; snowfall, Kochendorfer et al., 2022). As such, a large, distributed sensor intercomparison study would be necessary when integrating data across many sites, and instrument to instrument conversion factors may be estimated. Such a study would also be quite informative for research that relied on a specific sensor, as they would have a sense of how specific their results are to the sensor they used. Furthermore, working across CZOs allows us to evaluate the applicability of sensing technologies for earth science monitoring (e.g., drones, *in situ* gravimetry, air borne cosmic-ray neutron sensing, weighable high-precision lysimeter, eddy covariance, *in situ* isotopic tracing, fiber optic installations, environmental DNA and “omics”) to other contexts (e.g., mining, urban planning, wildlife monitoring, medical sciences).

4.3. *Examples of bringing CZ science into the Anthropocene*

There has been a broad recognition that we have entered into the Anthropocene, the era of human domination of earth’s ecosystems (Lewis and Maslin, 2015; Vitousek et al., 1997). Accordingly, there is a need to better understand how environmental science generally, and CZ science specifically, can better ask and answer questions related to human-environment interaction. Our final cyberseminar (CUAHSI, 2021b) addressed exactly this question. Abbott et al. (2019a) talked about the centrality of human interaction in the water cycle, and contrasted this centrality with the typically pristine representation of the global water cycle in literature, including scientific literature. For instance, human water appropriation equals about half of global river discharge, yet only 15 % of water cycle diagrams depict this interaction (Abbott et al., 2019b). In fact, the icon for the CZNet program in the US shows no human influences, despite a number of CZ sites being located in areas of intense human activity (agricultural or urban areas). Given that such diagrams are a point of entry to CZ for many people, both inside and outside of academia, recognizing and correcting this misrepresentation is an important step towards awareness and equitable development in the Anthropocene. While efforts in this direction have included updated diagrams on the websites of the Australian CZO network (https://www.tern.org.au/critical-zone/) and the OZCAR/Theia data portal (https://www.theia-land.fr/theiaozcar-un-portail-unique-dedie-aux-donnees-dobservation-in-situ/), only recently did the U. S. Geological Survey provide a radical update for its classic diagram of the water cycle, this time “with humans as showrunners” (Duncombe, 2022). Taking this viewpoint further, other cyberseminar participants talked about the importance of societal engagement and design approaches in CZ science. In particular, Arènes et al. (2018) highlighted that the CZ depiction to the general public is in the form of ‘planetary view’ of the Earth made familiar since the time of the scientific revolution and reinforced by the iconic image of the Blue Planet (Grevsmühl, 2014). Their work therefore tried to develop a different visual representation that captured the complex, heterogeneous and dynamic nature of the CZ to faithfully target practitioners and stakeholders that CZ scientists try to address through their science. They approached this through a unique collaboration between an architect, a sociologist engaged in the CZ field and a geochemist who heads the CZO network in France. This work has since been further extended into a book involving two architects and a science historian (Aït-Touati et al., 2019), and a museum installation that mimics a CZ observatory in Strengbach in France at a scale of 1:80 to adequately describe the design of the CZOs (https://critical-zones.zkm.de). Other examples of alternative representations of natural environments and processes following the same philosophical viewpoint are recent works from the Monsoon research group mapping rain (http://monass.org/, Bremner, 2021), the Forensic Architecture tracing chemicals in the atmosphere (https://forensic-architecture.org/), and the Italian Limes following the “moving border across Italy’s glaciers” (http://www.italianlimes.net/).

Other ways of societal engagement include Design Thinking, which includes a work process that puts users first and works through an iterative process designed to understand users and their problems, prototype solutions, test them, and iterate to arrive at better solutions (Liedtka, 2015). Goi and Tan (2021) suggested that Design Thinking must entail a deep understanding of the perspective of those it is aimed at, and thereby, could lead to more inclusive social innovations that involve stakeholders from various backgrounds. Their work also highlights the key role played by empathy with the example of constructing a map with audio guide to promote Ena City and its “noren” (split) curtains as Japanese culture. Finally, Marie Toussaint highlighted the importance of ecocide, and the importance of ensuring that human interaction with ecosystems is done in a way that allows ecosystems to renew themselves (CUAHSI, 2021b). Toussaint also highlighted that people who work directly with nature (e.g., farmers, hunters, indigenous peoples) know a lot about nature. Involving such people in CZO site selection, priority setting, and experimental design, could be quite valuable.

5. Challenges to a network-of-networks model

5.1. Insights from community feedback

To gather community inputs on the challenges and opportunities to conduct CZ synthesis and integration activities, we designed an online survey questionnaire. The explicit goal of the survey was to identify, define, and provide a stimulus for initiating integration and exchange of data, tools, models, and frameworks that enable cross-site cross-network analyses. The survey was conducted on a voluntary basis with participants from different CZO networks and single CZOs (Fig. 1**A**). Survey questions included available tools, simulation codes and openly available data, as well as perceived challenges associated with synthesizing across diverse CZ sites. We received a total of 130 responses from across CZO sites and networks (Fig. 2**A**), with respondents working across different agencies, institutions and disciplines. Based on this feedback, we identified several pressing needs and challenges that the CZ community are tackling related to integration and open sharing. Along with those pressing needs and challenges, the survey also highlighted what appeared to be major obstacles to the construction of cross-site cross-network collaboration (Fig. 2**B**). CZ respondents felt that key barriers to collaboration included “missing data harmonization”, “data access availability” and “lack of funding”. Additional obstacles were identified as the “lack of human connection” and “the environmental cost”. The time needed to build a trusting collaboration, parachute science and environmental justice issues were identified as “other” obstacles. Below, we describe in detail on how these obstacles constitute legitimate concerns for network-of-networks synthesis activities and solutions or partial solutions to navigating these concerns.

Survey participants identified ease of access to data from across CZ networks and harmonizing those data as key requirements for successful intercomparison of results across networks, sites, time periods and techniques. However, the accuracy and implementation of data collection techniques and tools vary depending on numerous aspects such as CZO type, the goal of the intercomparison study, and practical field constraints. While there are existing examples of data harmonization (e.g., Wieder et al., 2021) and existing portals of data targeting CZ research (see Section 4.1), an increasing emphasis on standardized data collection protocols, commonly-agreed upon data harmonization strategy and developments in cyberinfrastructure tools could significantly enhance opportunities for data discovery and cross-site cross-network collaborations.

Another obstacle to cross-site cross-network collaboration was highlighted as the lack of availability, accessibility or existence of funding to support international collaborations. While not abundant, some funding resources do exist. Classic examples that support such activities include the Powell Center and LTER synthesis proposals. Other examples include the Berkeley-France Fund (https://fbf.berkeley.edu/) or the German academic exchange service through DAAD (https://www.daad.de/en/), but these resources are limited to network exchange only. Some funding resources, while available, are restricted to specific disciplines such as iDiv for biology science (https://www.idiv.de/en) or techniques such as eddy covariance through the FLUXNET network (https://fluxnet.org/). In countries where a formal CZO funding source is itself lacking (e.g., Canada), it can be even more difficult to look for funding for international collaborations.

Given this background, it is evident that the CZ community needs to advocate for an international cross-site cross-network collaboration funded at a global scale, as is the case for the IODP (international ocean discovery program; https://www.iodp.org/) and the ICDP (international continental drilling program; https://www.icdp-online.org/home/). Examples of other funding setups include:

i) The European-funded COST actions: An example is the WATer isotopeS in the critical zONe (WATSON, https://watson-cost.eu), which focuses on building a European community around isotope-enabled tracking of water pathways in the CZ. It fosters knowledge exchange and new insights through a) funding short stays for visiting scholars and recurring workshops, b) encouraging building collaborative data portals and c) linking functional and spatial scales

ii) For arctic ecosystems (and more widely alpine/subarctic ecosystems) the INTERACT network can be used to fund field trip to stations over the northern hemisphere, but they also offer remote and virtual access to over 89 terrestrial field bases (https://eu-interact.org/)

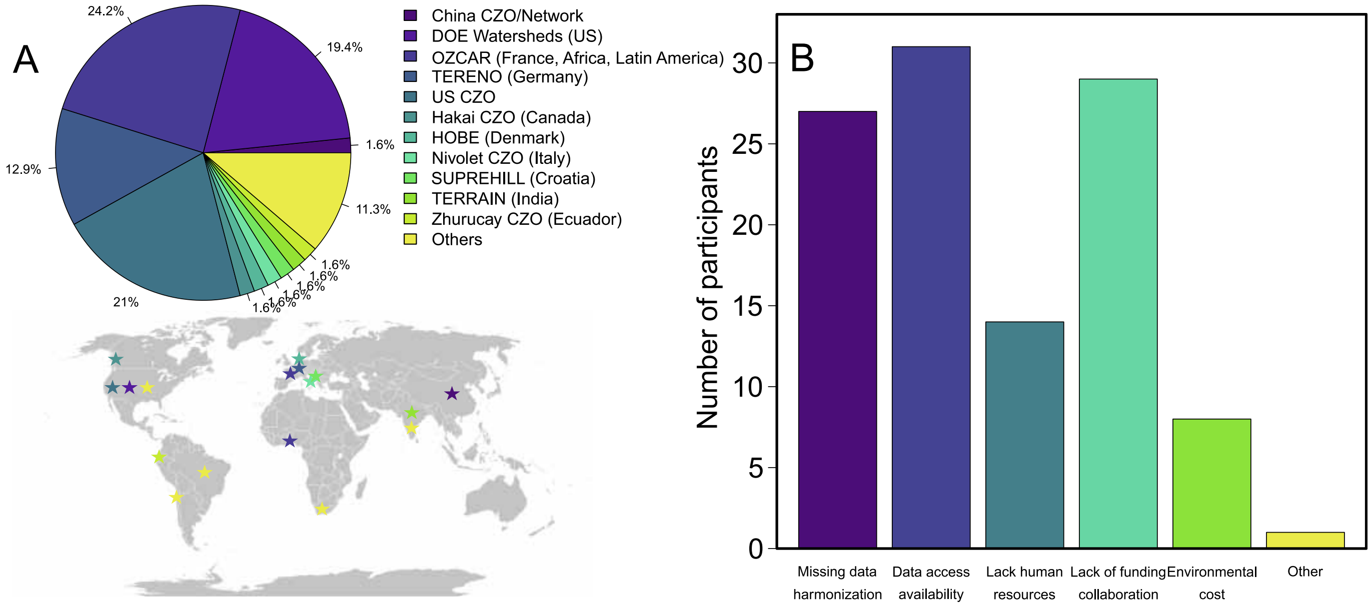

Fig. 2. (A) Overview of survey participants (130 participants) and their CZ network affiliation. (B) The primary obstacles to developing a cross-site cross-network collaboration as identified by the survey participants.

iii) The ERC synergy grants (https://erc.europa.eu/funding/synergy-grants) can go up to 10 M€ over 6 years and involve one non-EU co-PI.

While elements of collaboration and coordination can be achieved through these funding setups, we believe that the reach of the current CZ networks and the extent of scientific exchange could be vastly improved through a global network-of-network setup. Such programs could fulfill the urgent need for international funding to support CZ synthesis/integration activities at a worldwide scale.

Beyond the monetary and science-based obstacles, the survey also raised the fact that building a collaboration demands human-to-human interaction. Such interaction would promote interest in developing cross-cutting science questions that go beyond a single site and prompt discussions on transferability and interoperability of tools, data collection techniques and modeling frameworks. It is important to recognize that while social interactions can be easy in this day and age, developing personal connections can prove to be time-consuming and environmentally costly. For a socially-inclusive, global network-of-networks setup that promotes in-person interactions, navigating the environmental cost of travel can be a significant concern. And, this leads back to the need to advocate for an international collaboration funded at a global scale that supports this kind of expenditure but also promotes medium- to long-term engagement from relevant stakeholders, communities, and nonscientific experts to come together to understand and address CZ challenges. This solution could also partially address the still-existing problem of parachute science, occurring mostly in lower-income countries (Stefanoudis et al., 2021), and could entail a mandatory linking of external collaborators of the sites to the native collaborators for any experiments, building skills and valorization of works (conference, article, etc.).

5.2. Integrating social science with CZ research

Although not explicitly addressed through the survey, we believe that a close integration of social science with CZ science is critical to answering the most pressing challenges in CZ research. Because CZOs involve human habitats and human impacted areas, the need and establishment of a cross-site, cross-network collaboration should be used as an opportunity to intentionally and tightly integrate social sciences with CZ sciences. Barriers to such an integration have been highlighted as a combination of a lack of formal criteria emphasizing disciplinary research, cultural and career barriers, lack of linkage to industry, a conservative educational system and lack of strategic focus by universities (Holm et al., 2013). In fact, Holm et al. (2013) argue for a “revolution'' in education and capacity building that is deemed necessary in response to urgent environmental and social challenges. Indeed, there is increasing scientific evidence that human migration (Black et al., 2011) or social collapse can be due in whole (Zheng et al., 2014) or in part (Shaw, 2003) to environmental changes in the CZ (Scheffer, 2009). In tandem, an increasing number of IPCC reports are highlighting the impacts of climate change on human society (IPCC, 2001; 2007; 2014; 2022; etc.). Moreover, recent decades have highlighted that scientific understandings have often been poorly reflected in public policy and sometimes disregarded entirely when solely using a “supply-side model of science” (Oreskes, 2022). Together, these lines of evidence suggest an urgent need for integrating CZ research with human and social sciences. The human and social sciences encompass many disciplines, but in the case of integration with the CZ, a first level of integration should at a minimum include sociology (such as linkages with demographics and anthropological studies), political science (to integrate with public management aspects), economics and geographical science (e.g., studies of climate change impacts on the economics of societies and human migration), as well as human science such as history and archeology. To further this integration, such cross-disciplinary studies should be embedded in education programs. An example of such integration is the Earth Politics Center created in Paris in the Fall of 2019 that aims to address the complex issues of the Anthropocene by the convergence of natural and experimental sciences with the human and social sciences (https://u-paris.fr/centre-politiques-terre/en/the-earth-politics-center/). Likewise, there is emerging interest in community perceptions and attitudes to environmental change to promote communication of critical resources within the CZ and improve adaptive capacity. For example, Grunblatt and Alessa (2017) compared science-based assessment of environmental changes to society’s perceived notion of it, and showed diverse individual notions regarding the impact of humans on climate change. But, more importantly, Grunblatt and Alessa (2017) argued that these perceived notions can be changed through inclusive dialogue and engagement. An example where such dialogue is being facilitated is in a project called “Sentinelles des Alpes” set up by the Zone Atelier Alpes observation and research facility in France that specifically partners social researchers with local actors such as mountain guides, alpine hut keepers and/or regional parks workers. The project allows the sharing of experiences around important issues and the identification of potential avenues for synergies both in terms of research questions and more methodological aspects across 5 mountain socio-ecosystems, each led by a researcher and a local actor. This project resulted in a communication video to raise awareness on these alpine systems, which is also accessible to the general public (http://www.za-alpes.org/Le-programme-Sentinelles-des-Alpes). An example of where such human dialogue and connection will be important is urban CZ science. Including human dialogue in CZ science will allow us to question how humans and nature interact, whether new metrics ought to be sought, and what kinds of corresponding data should be collected about human activities in specific CZ areas, such as urban sites. It therefore clearly appears that in the current context of a society totally dependent on inevitable climate and environmental changes, the inclusion of human sciences as part of the CZ science is essential.

6. The path forward

6.1. Principles for enhancing cross-site cross-network collaboration in the CZ

In this section, we highlight the most important needs for enhancing integration/synthesis activities in the CZ as identified through the cyberseminar series and community feedback – 1) the need for open, standardized, global metadata; 2) the need for more efforts on data harmonization, and 3) the need for a new class of CZ data scientists. Going beyond technical innovations and towards collaborations in the CZ community, our main recommendation is to develop an open, inclusive, international network-of-networks framework that promotes the use of the “best available” science to address the most pressing challenges of the CZ.

6.1.1. The need for global metadata for CZ science

Ensuring cross-site cross-network CZ collaboration will require a number of technical innovations that have already begun, but require significant additional developments to help bring about open and networked science. Specifically, workflows are needed that enable data to be discovered, accessed, and harmonized. Data discovery refers to the ability to locate and understand data sets that exist, while access refers to the ability to obtain these datasets. In Section 4.1, we enumerated many CZ networks that made data available, and each one enables discovery across its own network. More and more of these networks structure their workflow and data life cycle requirements to make used data FAIR (findable, accessible, interoperable, reusable). The existing data portals work quite well when seeking to access data within one network. However, when integrating data across multiple networks, the existing approach is quite cumbersome, as one must learn the terminology, interface, and other aspects of every individual network. Moreover, data integration is particularly challenging in the highly multidisciplinary field of CZ science, due to the inherent diversity of the data that may be combined in a single portal, in both type (climate, ecology, geochemistry, genomics, etc.) and associated spatio-temporal scales (see, for example Table 2). Given this background, it is obvious that some kind of global catalog of networks is needed, and for this to be developed, some agreement on a harmonized metadata template is needed. This calls for having extensive metadata associated with the databases, ideally built in from the start in a robust data management plan, to avoid unforeseen discrepancies as the database grows. In practice, this implies making metadata generation and upload easy and user-friendly for data uploaders, and FAIR and open for the targeted users. Though not explicitly included in FAIR principles, the use of digital object identifiers (DOIs) for datasets and published algorithms has been an oft-mentioned need as well (CUAHSI, 2021a, 2021b). DOIs allow resources such as data or code to be unambiguously identified and cited, enabling much more transparency in research within and across networks.

6.1.2. *The need for semantics to power data harmonization*

Data discovery is simply a first step of working across networks. A much more difficult issue, and one that arguably has not been addressed as well as discovery, is that of harmonization. Harmonization refers to taking data sets from a number of different sources and having them conform to a particular schema for a particular purpose. Barriers to CZ data harmonization were discussed in detail in the second CUAHSI cyberseminar series (CUAHSI, 2021b). Todd-Brown et al. (2022) reported on an interview study with eight research group leaders who had constructed harmonized soil carbon datasets from pre-existing data. They found that while discovery tools were quite useful and available, there were virtually none dedicated to data harmonization. Harmonization was usually accomplished in a manual, ad-hoc manner, which proved to be quite labor intensive, error prone, and constituted no data provenance (detailed explanation of how the harmonized data was sourced from primary measurements). The data model that each group settled on for harmonized data tended to be dependent on the question they asked. This suggests that it is unrealistic to have a single data template or schema even for soil carbon work, let alone for CZ research. These results suggest the need for more research into data harmonization in CZ science. A generalized approach to data harmonization proved to be quite useful as shown in the SoDaH project (Wieder et al. 2021), where raw soil carbon data were annotated with a generalized metadata template. Such a generalized template allowed data to be mapped from whatever format they were collected into, to a format useful for a specific aggregated analysis, avoiding the need for a universal data storage schema. However, the specific templates employed in SoDaH were focused on soil carbon. Different questions and different source data may require a revisit to the templates used, should an approach similar to SoDaH be implemented more broadly.

These lessons learned in the soils field are likely to apply to the wider field of CZ science. If international CZ networks become linked together, we will need to develop ways to harmonize data across multiple schemas. For instance, the Theia/OZCAR network has opted to use a specific database schema for data across its network (Braud et al., 2020). It is quite possible that should a researcher wish to integrate OZCAR data with any other network's data, they would encounter harmonization difficulties similar to those encountered by Todd-Brown's (2022) interviewees. As a solution to this 'tower of babel' problem when working across disciplines, researchers have advocated for the use of formal ontologies (e.g., Sieber et al., 2011). Formal ontologies encode the domain knowledge of a community into a set of logical statements using classes, properties, and instances (Uschold and Gruninger, 1996). Importantly, formal ontologies are machine-processable and can be used for discovery and harmonization. Sieber et al. (2011) show how formal ontologies can be used for data discovery (and harmonization to some extent) across multiple databases of Chinese history. Wellen and Sieber (2013) question the use of formal ontologies of earth features due to significant natural language differences of those features. However, in a more restrictive context of sharing and harmonizing data across CZ networks, formal ontologies may be a useful tool. Nascent examples of such an ontology exist. For instance, the Open Biological and Biomedical Ontology (OBO) Foundry has an environment ontology (ENVO, Buttigieg et al., 2016) but it was not created to help scientists collaborate and is likely too broad for the purposes of CZ synthesis/integration activities. NASA's Jet Propulsion Laboratory has created an ontology of earth science concepts called SWEET (Semantic Web for Earth and Environment Technology; DiGiuseppe et al., 2014) that might be a promising start to a community ontology to enable data sharing and harmonization across CZ networks. Future research is needed to examine whether formal ontologies are appropriate underpinnings for data harmonization tools, or whether a schema driven approach such as the SoDaH project might be more appropriate, or whether other avenues may be needed.

6.1.3. *Towards a new class of CZ information scientists*

Given that data harmonization and integration were identified as a bottleneck for any CZ synthesis effort, and the highly multidisciplinary field of CZ science, the cyberseminar series (CUAHSI, 2021b) clearly highlighted the need for a new class of CZ information scientists. This meant involving scientist-users "in a hands-on way" in the design process of the data portals, working hand in hand with the database professionals to make sure that technical proficiency meets the users' needs. Community feedback from the survey further implied looking beyond researchers and actively engaging database users and creators, such as data scientists, managers and state agencies. Such synergies are expected to better connect long-term data portals with short-term and/or project-based data collection and may even incentivize data rescue, i.e. merging and harmonizing existing sparse records into a long-term dataset meeting the aforementioned standards. In the long-term, CZ science as a community of practice should integrate more advanced data literacy training for students and early career researchers. A move in this direction will help to develop a new generation of CZ scientists with a more holistic skillset.

6.1.4. *An open, international network-of-networks framework as a way forward*

To sustain CZ science into the future, we need an open, inclusive, international network-of-networks framework that helps overcome some of the issues that limit our progress. Such a framework is expected to not only promote synthesis/integration activities across CZ networks, but also open new sources of funding, build personal connections and human-to-human interaction, as well as engage CZ site managers and stakeholders at a level not previously accomplished. The inclusive and open nature of such a network is expected to better address inequalities in the sciences such as gender (e.g., Ranganathan et al., 2021) and ethnic and racial diversity (e.g., Bernard and Cooperdock, 2018) and improve the representation of women of color and white women in these fields, as well as promote ethnic and racial diversity. Networking with diverse stakeholders (e.g., women in science, underrepresented communities) is not only intended to create awareness regarding diverse needs, but to build partnerships that potentially contribute to more innovative ways of coordinating and sharing research. But, perhaps, more importantly, such a network is expected to leave behind a multigenerational legacy by training, educating and mentoring future CZ scientists, and act as a host for transferable tools, data and workflows (Fig. 3). Training for students and early career researchers as well as sharing of educational resources within this networking framework will be instrumental in propagating the novel tools, data and workflows developed herein. We expect such cross-network activities to at-a-minimum enable sharing of education materials, enhance engagement in cross-country Citizen Science projects, and increase participation in international summer schools. Consequently, a network-based approach is expected to enhance interpersonal interactions and establish career-spanning, collegial relationships and friendships. The power of such a network

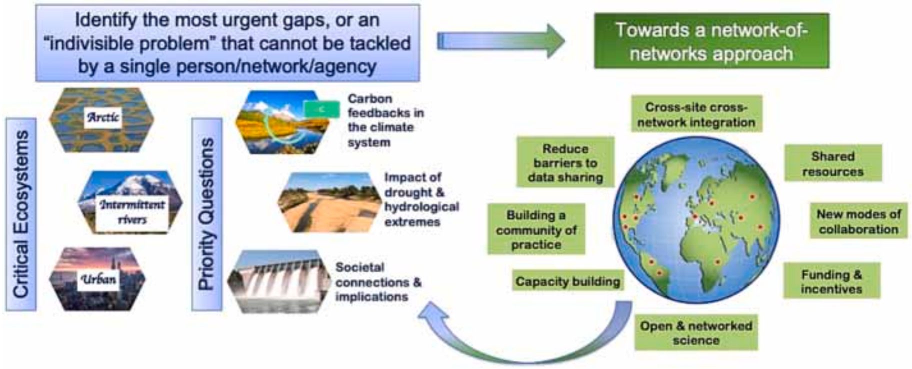

Fig. 3. Towards an open, international network-of-networks framework that can help resolve the most urgent gaps in rapidly changing ecosystems and enable next generation innovation in CZ science.

lies in its ability to mobilize people and further empower CZ students, early careers and scientists to pursue the pathbreaking questions that address the most complex as well as socially-relevant problems of our time.

One approach to facilitating a global network-of-networks framework is through the use of ICON science principles. These principles focus on the intentional design of research efforts to be "Integrated" across disciplines and scales, "Coordinated" through the use of consistent methods, "Open" throughout the research lifecycle (including publication of FAIR metadata and data), and "Networked" with a broad range of stakeholders to understand and respond to collective needs, priorities, perspectives, and risks (Goldman et al., 2022). For example, the Coordinated component of ICON is focused on intentional *a priori* planning and implementation of strategies to generate FAIR metadata and data that are generated in a standardized format as well as consistently structured upon publication. Further, these consistent protocols are expected to be Openly shared and framed based on multidisciplinary (i.e., Integrated) feedback/consensus (i.e., Networked). Using the ICON principles together is therefore meant to enable development of knowledge, data, and models that are generalizable or transferable across diverse settings.

Additionally, ICON is meant to enable research outcomes that are mutually beneficial across stakeholders, ranging from core research teams to land owners/managers to the general public. Producing research outcomes that are transferable and mutually beneficial does not happen by chance. It requires *a priori* planning and design, which can again be facilitated by using ICON principles to help build an international networks-of-networks for the CZ. Using a Networked approach is vital to this process, whereby open discussions and anonymous reporting across stakeholders can be used to understand needs and collectively work towards solutions. Although ICON can be applied to any scientific domain, it can be a particularly powerful tool for CZ science due to the diversity of systems, people, priorities, and limitations that need to be considered collectively to meet both fundamental and applied science challenges associated with the CZ. In this regard, the ICON Science Cooperative (https://www.pnnl.gov/projects/icon-science) is developing open resources to facilitate the use of ICON principles by researchers at any career or project stage (e.g., developing proposals, modifying existing projects). The CZ community can use and contribute to these resources to facilitate the intentional development of networks-of-networks and enhance the benefit of these efforts across a broad range of stakeholders.

6.2. *From observatory to living lab - using CZOs to address global societal challenges*

Many CZOs have been intentionally designed to monitor how human actions affect the coupled processes in the CZ (e.g., agricultural areas and managed watersheds), and herein, we propose that these individual sites and CZ networks together can help illuminate how humans affect the CZ across much broader gradients of climate, land use/management, and soil type than can be investigated at a single site. In this regard, a network of CZOs can provide important opportunities to identify the most urgent gaps, or an "indivisible problem" that cannot be tackled by a single person/network/agency, as well as address pressing science questions and societal challenges for many different environments (Fig. 3). For instance, the United Nations has set 17 sustainable development goals (UN SDGs) to address the challenges posed by human impact on many of the Earth's cycles including the water cycle (Abbott et al., 2019b) and CZ science is directly or indirectly relevant to many of these.

With a network of CZO sites in many different countries, it could be possible to treat a network of CZO sites as a 'living lab' where Design Thinking (see Section 4.3) and other approaches could be employed to inform policy development, management approaches, management tools, and other socio-ecological innovations in support of climate change issues, environmental sustainability and other relevant societal challenges. Indeed, CZOs may be ideal locations for inventing and prototyping new ideas regarding socio-ecosystem management, and cross-site cross-network collaborations could test more broadly ideas that are promising at a small number of sites. For instance, incentive programs to help farmers adopt conservation nutrient management have the potential to mitigate some issues associated with eutrophication of water bodies (Wilson et al., 2019), or promote sustainable water use that helps improve long-term water resources as well as reduce farmers' socioeconomic vulnerability (Fischer et al., 2022). One question that arises is how best to encourage farmers to do so? This requires both consideration of incentives (which differ drastically in different jurisdictions and contexts), the biophysical environment (which also differs), and through strong partnerships between the researchers and the community. A recent study on agroecological transitions in vineyards showed that the farmer's perception of risk could be mitigated by promoting environmental values as well as solutions to policy problems by including a team of ecologists and social scientists (Teschner and Orenstein, 2022). In another context, precision agriculture is becoming more ubiquitous in a wide diversity of sites, and has been the subject of comparison studies (e.g., Antle et al., 2017). Yet, there has been little work to evaluate how a move to precision agriculture may affect the overall functioning of the CZ. A network-of-networks framework can provide an important opportunity to close this gap by examining how human management decisions and adaptation strategies impact CZ functioning at a global scale.

Last, but not the least, a global network of CZO sites provides the necessary infrastructure to better understand the functioning of the CZ, and share resources, both of which are essential to tackle high priority science questions and societal challenges (e.g., Lü et al., 2017).

However, this must be followed by closer links between science, management and policy to improve decision making (Banwart et al., 2011). Hence, the understanding gained about CZ processes and functions, at a minimum, needs to be incorporated into quantitative decision-making tools designed to help environmental managers, stakeholders and policy-makers make decisions about adaptation and mitigation strategies (e.g., Banwart et al., 2013). Making this science-society integration will also crucially rely on the partnership with social sciences, as discussed in section 5.3.

7. Summary

Given the inherent diversity of CZOs and variability in governing CZ processes, a systematic approach to tackle these challenges is needed, with future efforts decreasing the fragmentation of individual CZOs and watershed sites as well as openly sharing data, models, and tools. Now, more than ever, there is increasing recognition that close coordination and integration across the global distribution of watershed sites and CZ networks can significantly advance science, provide opportunities to create a shared vision, learn from each other's mistakes, open doors for broad perspectives, and ultimately, address regional and national priorities. In this regard, a National Academies of Sciences, Engineering, and Medicine report (NASEM, 2020) made the case for an "all hands on deck" moment, defined as "*bringing together a demographically and scientifically diverse group of critical zone and watershed scientists, working both individually and in collaborative networks, to create and deploy cutting-edge analytical, computational, and field-based research methods in an open environment where success builds expeditiously on success*". The path forward should include more holistic, cross-site, cross-network studies that aim to advance our understanding of CZ and watersheds in response to environmental, technological, and societal changes, and build the next generation of tools that are broadly applicable and transferable.

There is an urgent need to build such a network-of-networks for several reasons. Firstly, increasing intensity and frequency of disturbances are pushing these systems to tipping points, such that the future functioning of these systems is uncertain with consequences for energy and water cycles, global distribution of nutrients, and human health (Armstrong McKay et al., 2022). A formal systematic (i.e., Coordinated) approach is therefore needed to work across these CZ sites and networks to develop a robust predictive understanding of how CZ and watersheds function and respond to compounding and co-occurring disturbances. Secondly, new techniques and technologies are providing observations that were previously not possible, such as eddy covariance-based measurements of N_2O and other trace gasses and fiber optic-based measurements of soil temperature, chemical and biological properties that can be useful indicators of global climate change (Baldocchi, 2014; Hubbard et al., 2020). Additionally, if these unique and novel watershed observations across networks/sites are to be analyzed through AI/ML-based approaches, such approaches hold the potential to transform our understanding, prediction and management of CZ/watershed behavior through the rapid identification of system tipping point precursors; the assimilation of diverse, multi-scale data into models for near-real time prediction and water management; and the ability for models to inform real-time optimization of autonomous sensing systems – from local to regional to global scales. Lastly, building on the success of these approaches and a formal global network-of-networks collaboration would significantly advance the understanding of environments that are extremely vulnerable and changing at a rapid pace - such as those associated with coastal regions, mountain watersheds, arid lands, agriculture, urban ecosystems, among others.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

We thank all presenters and participants of the CUAHSI cyberseminars for their insightful presentations and the rich discussions that followed, and partly motivated this opinion paper. They were Ben Abbott, Alexandra Arènes, Emma Aronson, Bhavna Arora, Vanessa Bailey, Jerad Bales, Holly Barnard, Laurie Boithias, Mikayla Borton, Isabelle Braud, Eoin Brodie, Nicolas Brüggemann, Goi Ho Chin, Louis Derry, Dipankar Dwivedi, Sylvie Galle, Ian Giesbrecht, Ciaran Harman, Sibylle Hassler, Steven Holbrook, Susan Hubbard, Andrew Ireson, Kathi Jo Jankowski, Xiaoxu Jia, Lixin Jin, Esteban G. Jobbagy, John Kominoski, Praveen Kumar, Melissa Lafreniere, Tanguy Le Borgne, Li Li, Gunnar Lischeid, Susanne Liebner, Philip Marsh, Holly Michael, Oliver Mogase, David Moulton, Michelle Newcomer, Xinhua Peng, Daniele Penna, Cristy Portales Reyes, Antonello Provenzale, Boqiang Qin, William Quinton, Victoria Quiroga, Matt Ross, Cody Ross, Muddu Sekhar, Chaopeng Shen, Heidi Steltzer, Kathe Todd-Brown, Laura Toran, Mark Torres, Marie Toussaint, Tao Wen, Stan Wullschleger, Fan Zhang, Yangjian Zhang, Liang Zhang, and Sam Zipper. The cyberseminars are viewable at CUAHSI's Youtube playlist (https://www.youtube.com/user/CUAHSI), specifically https://www.youtube.com/playlist?list = PLPG5Ed5L1SY7P5AVTVSnuvYCVfEq4JJJJ and https://www.youtube.com/playlist?list = PLPG5Ed5L1SY5AmJatGNZhUEppgtWKGy2x. We also thank Sarah Elizabeth Sharkey (Pennsylvania State University) for providing data on critical zone observatory locations and land use information from the Critical Zone Exploration Networks Site Seeker (https://www.czen.org/site_seeker). BA acknowledges funding from the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research (BER) for the Watershed Function Scientific Focus Area under Award no. DE-AC02-05CH11231. JS is funded by the U.S. Department of Energy-BER program, as part of an Early Career Award at the Pacific Northwest National Laboratory (PNNL). PNNL is operated for DOE by Battelle under contract DE-AC06-76RLO1830. JG is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - project no. 460817082.

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