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Invited Review Article

The meanings of the Critical Zone

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ABSTRACT

The original meaning of the Critical Zone (CZ) was spatial and pointed to one physical referent: the terrestrial surface of the entire Earth. As usage increased among researchers in the geosciences, social sciences, and humanities, new meanings led to the concept pointing to different places and ideas. Emerging trends have expanded the CZ further: CZs are mapped in computational spacetime and on distant planets and asteroids. The polysemous character of the CZ can be confounding for a field-based science, but Earth scientists and technologists have collaborated to collect and harmonize Big Data sets into a sizable library of CZ research in a short time (around 20 years). In this review, we map the semantic range of the CZ and explore how CZ science has remained coherent even as researchers diversified the concept by developing distinguishable but loosely overlapping meanings. We organize extant meanings into three tiers: (1) Earth's spatial interface of the geochemical and biological; (2) scientific knowledge of geophysical functionality of the CZ, as represented in an ever-growing library of data or by a single feature as proxy (e.g. soil); (3) a planetary home vulnerable to human disruption. In a time of immense human influence on the CZ, we underscore the latent meaning of planetary home, which marshals motivations of care and protection. These three tiers—the ontological, epistemic, and anthropocenic—build on each other to make the CZ a uniquely valuable concept for navigating the socio-ecological challenges of the Anthropocene.

1. Introduction

Earth science is the endeavor to generate knowledge about our planet's origin, evolution, and future. Beyond scientific curiosity, it is motivated by the need to maintain habitability in terms of food, fuels, freshwater, raw materials, and cultural connections (NRC 2001). This motivation has become acute in the "Anthropocene," the proposed geological epoch that began when human activities accumulated into geological force capable of disrupting the Earth system (Crutzen and Stoermer, 2000; Subramanian, 2019). In this context, the US National Research Council (NRC) established a cornerstone guideline to study the Earth's Critical Zone (CZ; NRC 2001). As a noun, CZ has referred to a place (i.e., the crust of the entire planet, not including oceans), study site in that place (e.g., a watershed), zone within a study site (e.g., the subsurface of a watershed), or the original place as the study site. As an adjective (e.g., CZ science), CZ has designated a model or methodology to study the CZ as a noun. These are the primary meanings of CZ; however, due to the broadness of Earth science and interdisciplinarity of CZ research, additional meanings have since been introduced (Giardino and Houser, 2015).

Now CZ points to different places on Earth, which is potentially confounding for a field-based science. Adding further confusion, CZ has different meanings in some geoscientific disciplines, which sets additional CZs inside the CZ of the NRC definition (Fig. S1). Many researchers note this confusion (Lin, 2010; Chamorro et al., 2015; Gamache et al., 2015; Giardino and Houser, 2015; Brantley et al., 2017a, 2017b; Lu et al., 2017; Xu and Liu, 2017; Arenes et al., 2018; Aguilar et al., 2020; Singha and Navarre-Sitchler, 2021). One possible remedy is to settle on a definition that is overarching. For example, CZ has been defined as representing the *spirit of system science* (Lin, 2010; Giardino and Houser, 2015; Ashley, 2020). However, it remains unclear what the physical boundaries of the system(s) are, and how diverse communities

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of researchers study, let alone communicate about, these system(s).

As the CZ concept garners significant attention and reaches international status, it is important to step back, survey, and make sense of its polysemous character. We reviewed 153 articles selected for (a) the centrality of the CZ in each and (b) their collective representation of geoscientific, social scientific, and humanities approaches to Earth science. For each article, special attention was paid to the assumed or stated conception of the CZ. Our general methodology was the scoping review, which maps relevant evidence in a comprehensive overview of the literature to clarify concepts and identify knowledge gaps (Peters et al., 2021). Because the CZ concept is relatively new, more specific questions (i.e., those requiring precise syntheses of statistical or qualitative data) have yet to be identified and explored, making a scoping review particularly valuable (Munn et al., 2018).

In our overview of the CZ's semantic range, we distinguish and relate three tiers of extant meanings. First-order meanings specify ontological dimensions: a global physical surface demarcated by spatial boundaries and comprising many sites where life-generating processes interface. In response to the complexity of research grounded in first-order meanings, second-order meanings equate the ontological CZ with the epistemic CZ represented in the ever-growing library of data collected on the (ontological) CZ. Commonly, researchers use one specific feature (e.g. soil, bedrock, or surface water) as a proxy standing in for the spatial CZ in its entirety. Finally, third-order "anthropocenic" meanings emphasize the pragmatic, affectual, and timely dimensions of the CZ: with enhanced data and synthesis (epistemic) of its complex interactions and spatial presence (ontological), the CZ's provision of a large-scale habitat and home for human and more-than-human life becomes clear along with the realization of its vulnerability to human disruption. These tiers have developed organically and rapidly to make CZ a planetary concept that is scalable in space, dynamic in time, responsive to societal needs and impacts, and thus particularly suited for navigating the challenges of the Anthropocene.

2. First-order meanings (ontological): CZ as life's place or the processes sustaining it

When the Critical Zone was coined, two definitions were given and since then the CZ has been referred to by both interchangeably, causing confusion. In the first definition, the CZ is "the land surface and its canopy of vegetation, rivers, lakes, and shallow seas, [extending] through the pedosphere, unsaturated vadose zone, and saturated groundwater zone" (NRC 2001; Fig. 1a). Here CZ means a singular place, referent, and study site, defined geometrically in the common sense of Euclidian space. The area is fixed as the terrestrial surface of the planet, whereas the thickness varies at a given location and at multiple temporal scales (Ashley, 1998; NRC 2001; Amundson et al., 2007; Brantley et al., 2007; Lin, 2010; Rowley et al., 2015; Brantley et al., 2017b; Arenes et al., 2018; Gaillardet et al., 2018; Ashley, 2020; Sajjadi et al., 2020), depending on vertical parameters, such as the height of treetops (e.g., a hundred meters above the surface) and depth to bedrock (e.g., a kilometer or more below the surface). Despite the variability, the geometric dimensions of the CZ can be estimated (the thickness of the CZ was estimated to range from 0.7 to 223.5 m with an average value of 36.8 m across continental areas [Xu and Liu, 2017]). In the second definition, emphasis is placed on the interactions that "determine the availability of nearly every life-sustaining resource" (NRC 2001). This second meaning is useful because it turns the focus from the areal to the vertical dimension, highlighting important interactions among layers of rock, soil, water, air, and living organisms (Fig. 1b): (Chorover et al., 2007; Lin, 2010; Guo and Lin, 2016; Arenes et al., 2018; Luo et al., 2019).

When referred to by this second definition (life-sustaining resources), CZ typically means a more spatially-limited, abstract, or physically-agnostic (e.g., defined by political rather than hydrologic processes) zone, such as a single (or multiple) watershed, basin, ecosystem, biome, country, or some other area that is distinctly different from the first definition (crust of the planet). To reconcile this, the first definition (crust of the planet) can be re-conceptualized as meaning the collection of all sub-planetary areal divisions. Then, inversely, a single sub-planetary area is implied to be only a part of the CZ. Therefore, there is only one CZ, but manifold ways to define or emphasize its parts. This gives CZ consistency so that both meanings of CZ can be used interchangeably. Importantly, this facilitates movement in scale, allowing researchers to study processes across large scales of space and time, from the development of landscape heterogeneity (pedogenic and geomorphic time scales) to CZ system dynamics (biotic colonization and hydrologic event time scales; Brantley et al., 2007; Quijano and Lin, 2014; Pelletier et al., 2018).

Ultimately, both meanings are used together: process-based studies are integrated to understand the CZ piecemeal (Ashley, 1998; Brantley et al., 2017b) because analyzing the CZ at the planetary scale provides valuable benefits over analyzing it at the scale of parts (Brantley et al., 2016). Biomes that are structurally diverse and geographically distant from each other (e.g., glacial and periglacial landscapes [Gamache et al., 2015; Rowley et al., 2015], coastal barriers [Barrineau et al., 2015], estuarine and coastal wetlands [Liu et al., 2021], deserts [Tchakerian and Pease, 2015], and intermittent rivers and ephemeral streams [Fovet et al., 2021]; Fig. 2) are represented, so mass balances can be calculated, processes elucidated, and actors accounted for across the whole Earth. This allows researchers to nowcast and backcast in order to forecast

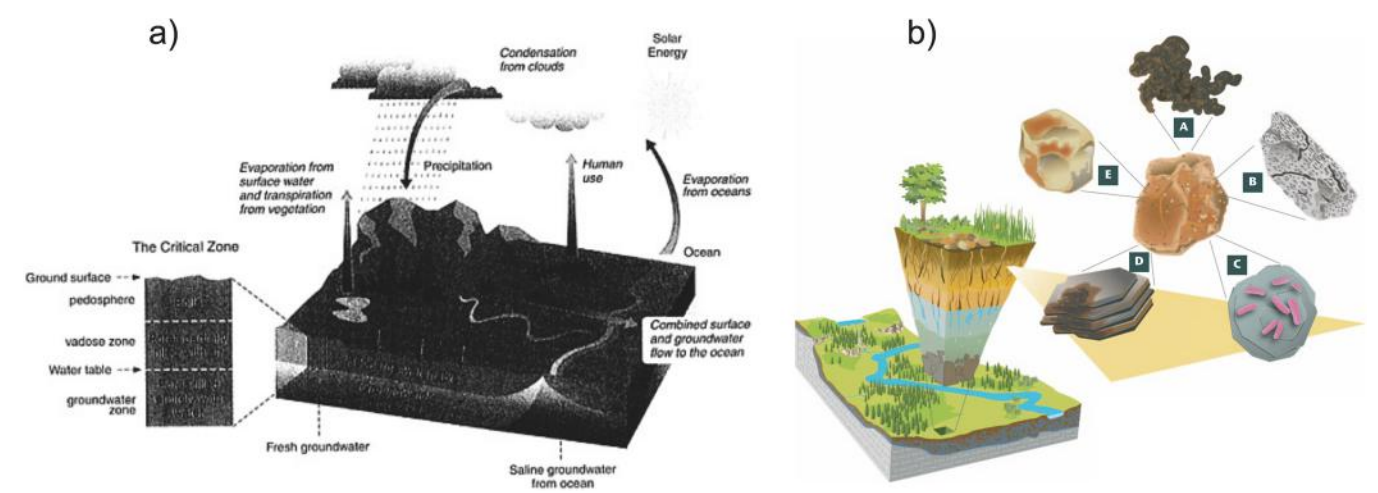

Fig. 1. Conceptual models defining the Critical Zone as a place. a) NRC (2001 [Fig 2.1]) emphasizes the horizontal expanse of the CZ at the scale of the terrestrial surface area of the planet. b) Chorover et al. (2007) [Fig. 1]) emphasize the interactions of the vertical layers of the CZ at the scale of a sub-planetary area.

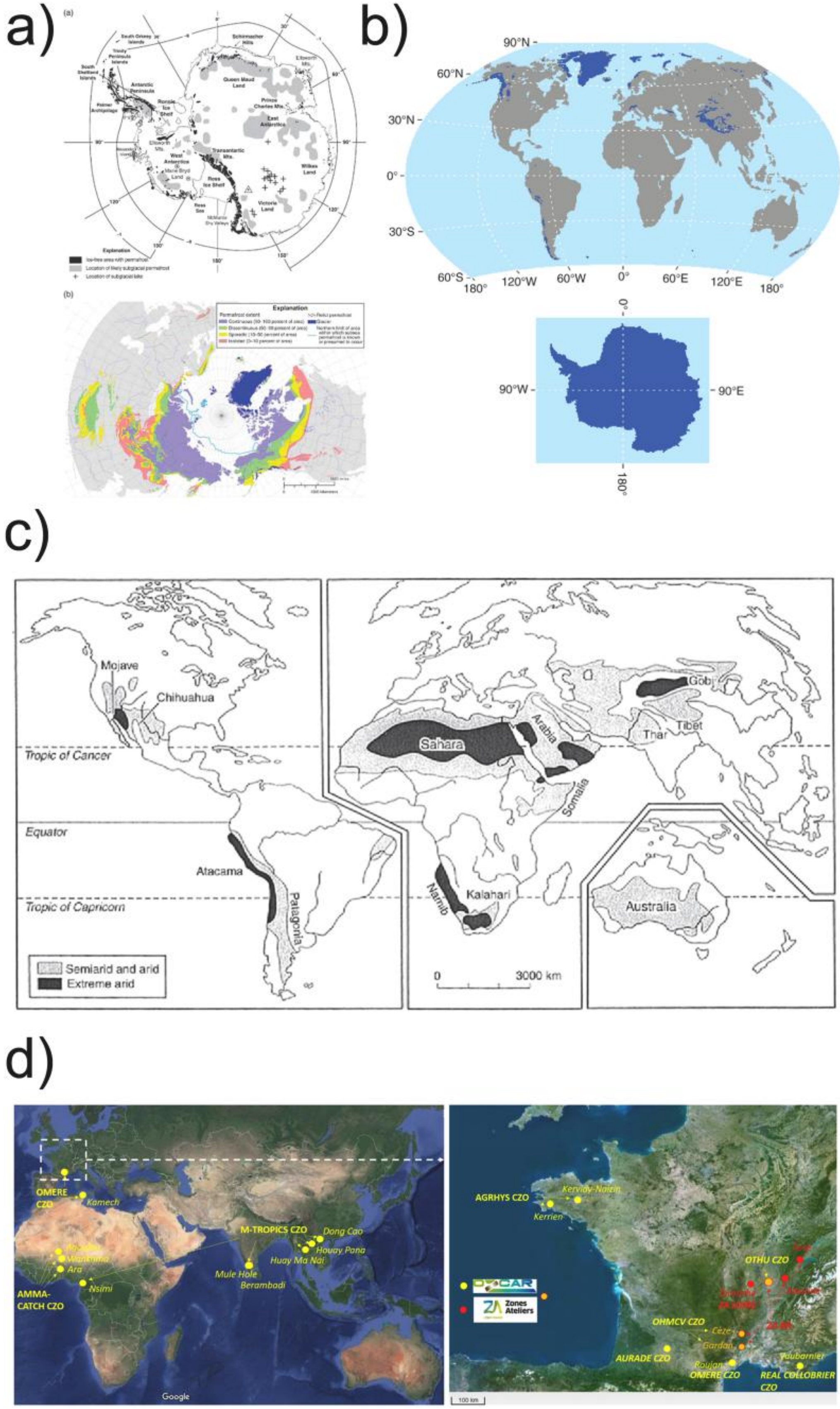

Fig. 2. Diverse and distant biomes across the Critical Zone include a) permafrost (Rowley et al., 2015 [Fig 13.2]), b) glaciers (Gamache et al., 2015 [Fig. 12.2]), c) deserts (Tchakerian and Pease, 2015 [Fig. 14.1]), and d) intermittent rivers and ephemeral streams (Fovet et al., 2021 [Fig. 1]).

specific phenomena (Giardino and Houser, 2015), and then to earthcast (i.e., project how the total environment will evolve by using mechanistic models that capture the essential phenomena, as well as by applying scenarios of human behavior; sensu Godderis and Brantley, 2013; Duffy et al., 2014).

3. Second-order meanings (epistemic): CZ as the product of collaborative synthesis

In its second tier of meanings, the Critical Zone is seen as only the place where there is reliable data on the various fluxes of ingredients flowing through it (Latour, 2014). This perspective changes the CZ from a physical referent to a higher-order concept. The CZ is then represented as a kind of library, a sustainable and enduring digital space where data and literature are shared to enrich contemporary users and posterity.

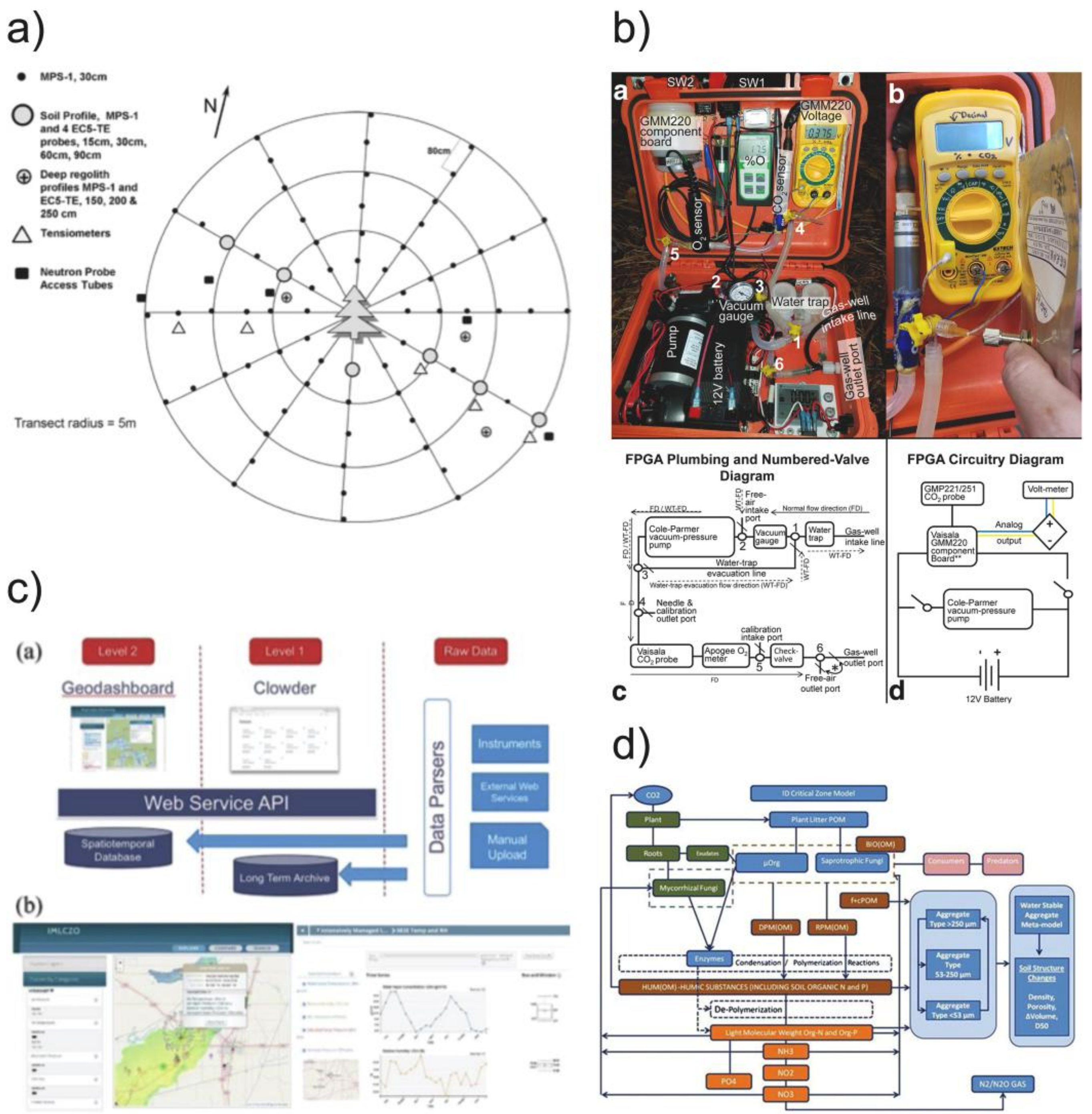

Fig. 3. Novel sensing methods and information technologies developed at different Critical Zone Observatories include a) extensive sensor networks at the Southern Sierra CZO (O'Geen et al., 2018 [Fig. 8]), b) Field Portable Gas Analyzers at the Calhoun CZO (Brecheisen et al., 2019b [Fig. 2]), c) a data management system at the Intensely Managed Landscapes CZO (Wilson et al., 2018 [Fig. 8]), and d) a conceptual model (CZ Integrated Model) of carbon and nutrient flows, which incorporates a numerical model (Carbon dynamics and Aggregate STability [CAST]) of soil aggregate formation and degradation processes, at multiple CZOs (Banwart et al., 2012 [Fig. 11]).

This meaning motivates and guides advances in generating remote, in situ, and in silico data, with library construction depending on funding mechanisms and research methodology. It brings together many Earth scientists and technologists from different disciplines (Brantley et al., 2007) to develop the necessary data infrastructure in a process envisaged in the same article in which the CZ was coined (NRC 2001; Brooks et al., 2015; Fovet et al., 2021). As new sites are studied, the CZ expands.

3.1. CZ defined as a model of collaboration

Many precursor programs collected data on the environment before CZ was coined (see White et al., 2015; Brantley et al., 2017b), but none combined subsurface processes with surface and surface-atmosphere interactions in an integrated approach (Lin et al., 2011), partly because the power of available technological tools was not commensurate with this need (Giardino and Houser, 2015). Soon after CZ was coined, researchers met at a workshop to plan a network of observatories, staff, and instrumentation that would study the CZ (Brantley, 2006). Since 2007, the National Science Foundation has organized nine specific CZ observatories (CZOs) in diverse landscapes across the US—these were natural watershed laboratories selected for investigating Earth surface processes mediated by freshwater (White et al., 2015). Characteristics of a CZO include long-term operations to quantify controlling mechanisms; hypothesis-testing (not simply monitoring); extensive sensing and sampling methods that incorporate multidisciplinary research across timescales; compilation and sharing of large data sets; and development of mathematical, numerical, and, ultimately, conceptual models that extend the scientific endeavor (Banwart et al., 2011, 2013; Brantley et al., 2017b).

3.1.1. Collaboration among sensing, information technology, and computational communities

The sensing and sampling communities were motivated and guided by the Critical Zone vision (Fig. 3). For example, at the Southern Sierra Critical Zone Observatory, extensive sensor networks were established to measure water dynamics at the soil profile, hillslope, and watershed scales, thus revealing the complexity of interactions among all aspects of the water balance (runoff, storage, evapotranspiration, and precipitation) at daily, seasonal, and annual time scales (Fig. 3a; O'Geen et al., 2018). At the Calhoun CZO, novel methods were developed using Field Portable Gas Analyzers to capture in situ aerobic respiration occurring deep in the soil (Fig. 3b; Brecheisen et al., 2019a). At the Luquillo CZO, stable isotope and chemistry data were collected and analyzed to infer weathering along deep bedrock fractures (Lara et al., 2014).

Novel, high-resolution multispectral/multitemporal imaging techniques were used to fill in gaps between time-consuming point measurements in spatial data sets (Bishop et al., 2015; Parsekian et al., 2014). For example, to image the structure of the subsurface (0–20 m depth to bedrock) at the Boulder Creek CZO, a shallow seismic refraction method was used (Befus et al., 2011). At the Luquillo CZO, a combination of direct drilling and ground penetrating radar was used (Orlando et al., 2016). To image the surface, researchers met at a workshop to discuss using Light Detection and Ranging (LiDAR) data and technology (Harpold et al., 2014). LiDAR incorporates simultaneous measurements to account for natural topography, above-ground vegetation, built infrastructure, exposed bedrock, stream channels, and snow/ice (Harpold et al., 2015). At the Calhoun CZO, a methodology using LiDAR data and a set of algorithms was developed to detect and map gullies to estimate erosion automatically (Noto et al., 2017). At the same CZO, LiDAR data and microtopographic terrain roughness analyses were used to infer historical land use and management (Brecheisen et al., 2019a).

Intensive measurement efforts at the CZOs produced Big Data (i.e., extensive data sets that are structurally heterogenous, and produced at high velocity in large volumes; Gandomi and Haider, 2015), which required information technology systems to collect, structure, archive, and deliver that data to end users in real-time. Researchers met at a workshop to develop an ontology for a consistent data, metadata, and cyberinfrastructure system (Hofmockel et al., 2007). As a result, data infrastructures were built (e.g., Wilson et al., 2018; Fig. 3c) coincidentally with innovations in internet connectivity, multimedia information processing, data storage, and visualization techniques (NRC 2001). Also coincidentally, FAIR (findability, accessibility, interoperability, and reusability) Data Principles were published to support the reuse of scientific data (Wilkinson et al., 2016). These principles have been adopted increasingly in data repositories and observational work, and promoted even more broadly across all areas of science (NAS 2018; NAS 2019).

The creation of Big Data sets led to calls from researchers to couple reactive transport numerical models with other community models to explore the interactions among fluxes of water, material, and energy in the CZ (Li et al., 2017). Given the complexity of the CZ, no single numerical model can simulate it, so groups of models were developed, then coupled and parameterized by Big Data sets (Duffy et al., 2014). Models (e.g., numerical models of soil aggregate formation and degradation [Fig. 3d]; (Banwart et al., 2012, 2017; Giannakis et al., 2017), and mathematical models of carbon and water fluxes [Chorover et al., 2011]) were successful and, in turn, could produce synthetic data to fill in gaps in the empirical data sets, thus adding to the Big Data.

3.1.2. Harmonizing Big Data

The use of these Big Data and metadata was and remains challenging because of their size, diversity, and complexity (Brantley et al., 2017b). Nevertheless, Big Data has been harmonized successfully in many studies to develop deep, process-level understanding across spatiotemporal scales. For example, at the Susquehanna Shale Hills Critical Zone Observatory, field samples, empirical measurements, LiDAR data, national databases of hydrologic, meteorological, and phenological data, and other data collected from previous research at the site were all harmonized to parameterize a reactive transport model at the watershed scale (Wen et al., 2020). Researchers showed that the study watershed produces and stores dissolved organic carbon (DOC) under hot and dry conditions, but switches to exporting DOC under cold and wet conditions. At the same CZO, other researchers focused on soil production rates, which were determined using uranium-series isotopes at the hillslope scale (Ma et al., 2013). In a companion study, soil production and downslope transport across hillslope transects were characterized using meteoric beryllium (^{10}Be) measurements from regolith and bedrock (West et al., 2013). Then simple numerical models of soil production and erosion were calibrated to these data and determined that regolith production and erosion rates are similar. Also at the same CZO, other researchers focused specifically on one zone—the subsurface. Multiple water tables, which were shallow (characterized by soil interflow) and deep (characterized by flow through weathered and fractured bedrock), were found consistently across sites despite significant differences in bedrock lithologies, geomorphologic characteristics, and land use (Li et al., 2018a).

Some researchers investigated CZ hydrology by focusing specifically on the surface and shallow subsurface. At the Intensively Managed Landscape CZO, soil and stream solute behavior in two watersheds of mixed land use were explained by agricultural activities (Dere et al., 2019). At the same CZO, transport of sediment and dispersal of microbes were characterized by accounting for land use at the surface and runoff in the combined surface and subsurface (Wilson et al., 2018). At the Boulder Creek CZO, soil cores were collected and manipulated to investigate impacts of simulated fire followed by simulated rainfall on field-saturated hydraulic conductivity, dry bulk density, total organic carbon, and infiltration processes (Wieting et al., 2017). Other researchers focused on the deep subsurface. At the Eel River CZO, differences in underlying lithology explained distinct water storage limitations and, in turn, distinctly extensive plant communities under a similar climate (Hahm et al., 2019). At the Reynolds Creek CZO, the water balance was calculated in a watershed where water flowed from upland sources to stream channels via flow paths multiple meters below the ground surface (i.e., below the depth of typical soil instrumentation and characterization; Seyfried et al., 2018).

3.1.3. Expansion of the CZO model to other nations

Critical Zone Observatories were the initial nine lenses through which the Critical Zone was studied. In 2014, the CZO National Office was created to facilitate CZO network-level research and outreach

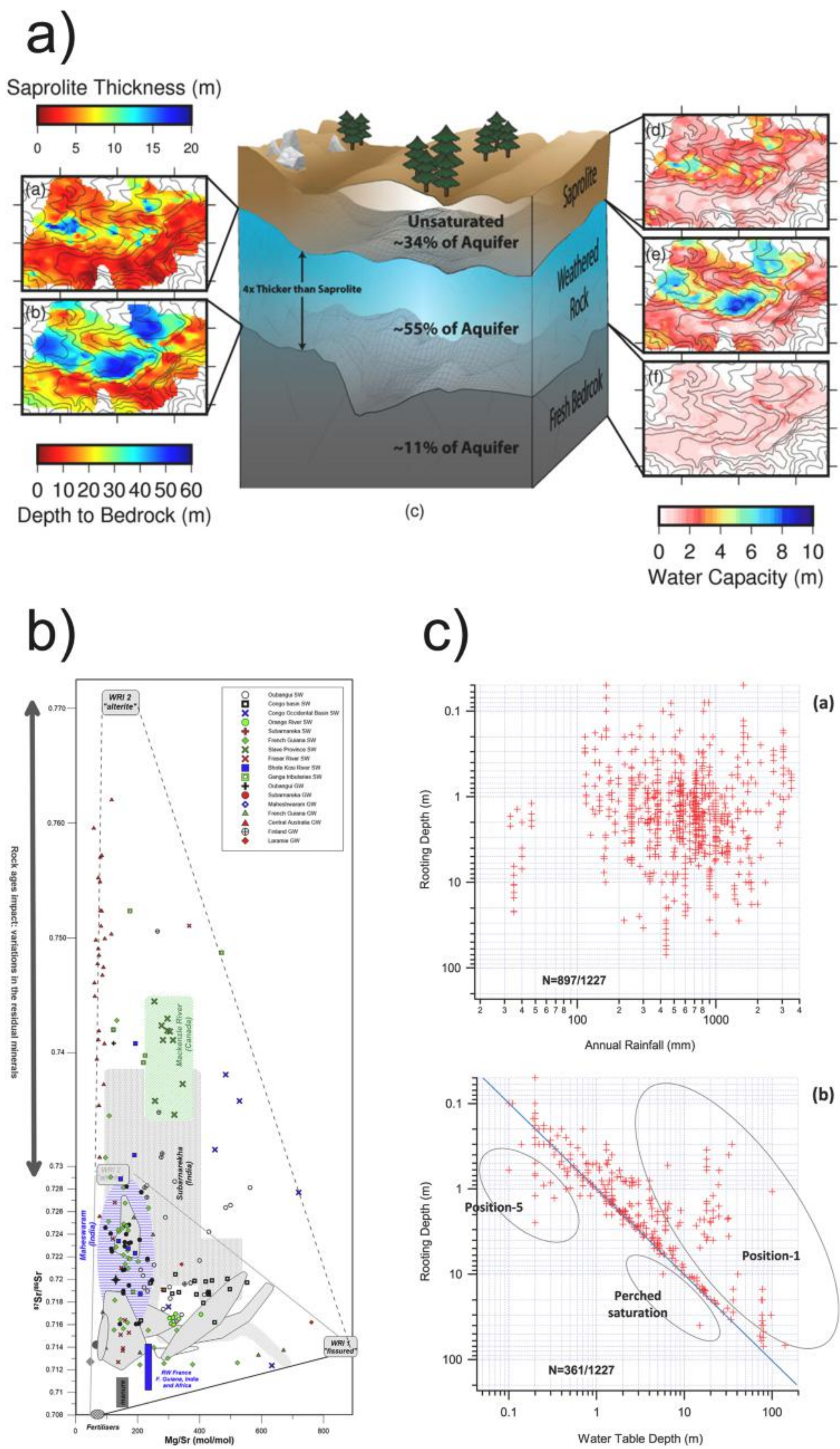

Fig. 4. Critical Zone research at study sites that are not official Critical Zone Observatories. a) Water storing capacity of a high mountain watershed in the Laramie Range in Wyoming (Flinchum et al., 2018 [Fig. 12]). b) Strontium isotope ratios vs. magnesium/strontium ratios in subsurface water in watersheds in Africa, India, Nepal, North America, South America in French Guiana, Europe, and Australia (Negrel et al., 2018 [Fig. 9]). c) Relationships among precipitation, water table depth, and plant rooting depth in a meta-study of 1227 studies around the world (Fan, 2015 [Fig. 5]).

activities (White et al., 2015; Richardson, 2017). Some researchers started conducting studies that compared multiple CZOs (e.g., Miller et al., 2016). Also, researchers everywhere called for further expansion from a national (US) to a global network of CZOs (White et al., 2015; Guo and Lin, 2016; Wymore et al., 2017; Zhang et al., 2019b), which would combine the parameter space across all existing and new CZOs so that the CZ could be studied as a single entity (Lin, 2010; Brantley et al., 2017b; Richardson, 2017).

CZ became a fashionable concept as many nations established CZ programs with their own strategies (Giardino and Houser, 2015). Although not all international observatories are explicitly called CZOs, they were created under the framework of CZ science (White et al., 2015; Richter and Billings 2015; Richardson, 2017) and met a significant requirement to work with the US-established CZOs (Banwart et al., 2013). In Germany, an artificial watershed (Chicken Creek Catchment) was constructed with CZ elements, then instrumented extensively (Gerwin et al., 2010). In contrast to other CZOs with long-term data sets, this allowed researchers there to study an early-stage ecosystem with highly dynamic properties as it goes through natural primary succession (Huttl et al., 2014; Schaaf et al., 2017). As in the US, the establishment of international CZOs led to new sensing methods and computational infrastructures. For example, at French CZOs, data users, data producers, and information technology teams consulted with each other to develop a common information system (Theia/Observatories de la Zone Critique– Applications et Recherches Information System) that facilitates archiving of their in situ observations while also making their data compliant with FAIR principles (Braud et al., 2020). By 2015, 64 CZOs had been established in more than 25 nations worldwide (Giardino and Houser, 2015), some as distant as the Qinghai Lake Basin CZO in permafrost China, also known as the “third pole” (Li et al., 2018b). There is high interest among other countries (e.g., Canada; Martin and Johnson, 2017) in developing CZO programs.

The concerted network of CZOs worldwide allowed researchers to develop a more comprehensive understanding of a given physical system by studying that system across a wide range of spatiotemporal scales and under different geological, geomorphological, climatic, and soil cover settings. For example, karst watersheds and aquifers represent a major source of drinking water around the world (Dai, 2021). At the Koiliaris CZO in Greece, exogenous tidal fluctuations were found to have a significant effect on the water budget and flow paths of a karst watershed, making it necessary to study the system at a spatial scale larger than a single watershed (Lilli et al., 2020). In China, there has been rapid loss of soil across karst landscape resulting in rocky desertification, making it necessary to study the effects of widespread intensive agriculture (Green et al., 2019). At the Puding Karst CZO in China, continuous high-frequency monitoring of a spring outlet revealed that most hydrochemical variables responded to hydrologic variations, but were also influenced by mixing of different upstream sources where various biogeochemical processes occurred (Qin et al., 2020). At the same CZO, nitrogen cycling was characterized by calculating denitrification rates in soils that were severely degraded then revegetated (Li et al., 2021). At the French Karst National Observatory Service, karst systems are studied at the watershed and larger aquifer scales across a network of CZOs in different physiographic and climate contexts (Jourde et al., 2018).

3.1.4. Expansion of the CZO model across the CZ

There was widespread advocacy for (Liu et al., 2021) and adoption of the Critical Zone Observatory model, thus signifying a community shift in methodology that effectively multiplied the number of CZOs (Fig. 4; Richardson, 2017; Liu et al., 2021). The CZO model was emulated by networks of researchers, such as the US Geological Survey (Graf, 2004), the Department of Energy’s Terrestrial Ecosystem Science program (White et al., 2015), and the International Long Term Ecological Research system (Muelbert et al., 2019), all of which have existing research infrastructure, employ standard data protocols, and are committed to free and open data sharing and interoperability. The CZO model was emulated also by many individual researchers across the US at their study sites (i.e., not official CZOs). For example, in the Laramie Range in Wyoming, novel geophysical techniques were used to estimate soil porosity and determine the water storage capacity in a study watershed (Flinchum et al., 2018; Fig. 4a). At the Santa Rita Experimental Rangeland in Arizona, comprehensive long-term (13 y) measurements were made to calculate the water balance in a semiarid savanna (Scott and Biederman, 2018). At the Konza Prairie Biological Station in Kansas, climatic, ecologic, and hydropedologic data were harmonized to form a comprehensive understanding of the aquifer and provide the basis for predicting future landscape evolution (Vero et al., 2018).

Internationally, the CZO model was emulated also by individual researchers. In watersheds in Scotland, Canada, and Sweden, water balances were calculated by harmonizing large data sets that captured multiple eco-hydrological processes across vertical layers (Sprenger et al., 2018). In another study in Sweden, geometry, discharge rates, and material properties of the widely studied S-Transect hillslope within the Krycklan watershed were used to produce theoretical models of primary weathering rates, water transit times, and concentration-discharge (*C-Q*) relations (Ameli et al., 2016). In watersheds in France, India, Nepal, North America, South America in French Guiana, and Australia, strontium stable isotope and magnesium/strontium ratios were used to investigate the impact of rain, agricultural practices, and water-rock interactions in shallow and deep groundwater (Negrel et al., 2018; Fig. 4b). In semi-arid woodlands in Australia, eddy covariance data, phenocams and airborne imagery of vegetation, soil moisture data, and intact soil cores were harmonized to determine how soil moisture mediates the phenological response to precipitation (Cleverly et al., 2016).

This independent research (i.e. not conducted at an official CZO) often complemented the research at official CZOs. For example, the Puding Karst CZO is in Guizhou Province in southwest China. In addition to research at that CZO, other researchers studied the entire Guizhou Province, exploring the importance of bedrock geochemistry on vegetation productivity. These researchers concluded that accounting for the formation of crevices in bedrock and subsequent leakage through regolith can predict vegetation productivity (and thus transpiration) more effectively than previous models (Jiang et al., 2020). Other researchers developed models across southwest China, harmonizing remote sensing, GIS analyses, and field surveys to explain the mechanisms causing soil loss and landscape degradation (Zeng et al., 2018).

Individual researchers began making essential advancements in technological methodologies, such as near-surface geophysical instrumentation (Parsekian et al., 2014). A growing number of studies use active source shallow seismic refraction to characterize the subsurface structure at a study site. However, measurement uncertainty and model resolution at depth are generally not evaluated, making it difficult to identify and interpret CZ features conclusively. At Rancho Venada in California, researchers developed a seismic velocity inversion strategy for near-surface geophysics that does not require regularization parameters, such as model smoothing or damping, and that more fully quantifies model uncertainty (Huang et al., 2021). In the Laramie Range in Wyoming, researchers developed a method to measure shallow seismic anisotropy using geophones (Novitsky et al., 2018). They inferred remnant fracture orientations at ~2–4 m depth that agreed with brittle fracture orientations measured at tens of meters depth in boreholes, thus demonstrating that bedrock fractures persist vertically into the shallow CZ. In southern British Columbia, researchers mapped the thickness of the pedosphere on a landscape scale (~3400 km^2) using four statistical methods (Generalized Linear Model, Random Forest, Generalized Linear Model Residual Kriging, and Random Forest Residual Kriging) to make a model out of spatial data layers derived from a digital elevation model and satellite imagery (Scarpone et al., 2016). Other researchers studied the CZ at the planetary scale by using Earth systems models (ESMs) and global data sets (Fan, 2015; Fig. 4c). Though ESMs are derived from General Circulation Models of the atmosphere, codes have been written to account for dynamic processes in oceans and on land, and there is promise of extending ESMs deeper into the terrestrial subsurface.

3.2. CZ represented by different proxies or unifying threads

The accumulation of Critical Zone studies gave scientists knowledge of geophysical processes at the larger spatial and temporal scales that were originally envisioned and necessary to meet the aims of the NRC. Synthesis of the CZ library became a possibility and a priority. One apparent approach was to identify a single unifying thread that could be treated as coextensive with, i.e., as a proxy for, the CZ itself. This unifying thread explains the geophysical function of the CZ by combining the second-order (methodological advances; epistemic) and first-order (spatial reference; ontological) meanings. Many proposals of a thread were made, including a particular organism, zone, compound, element,

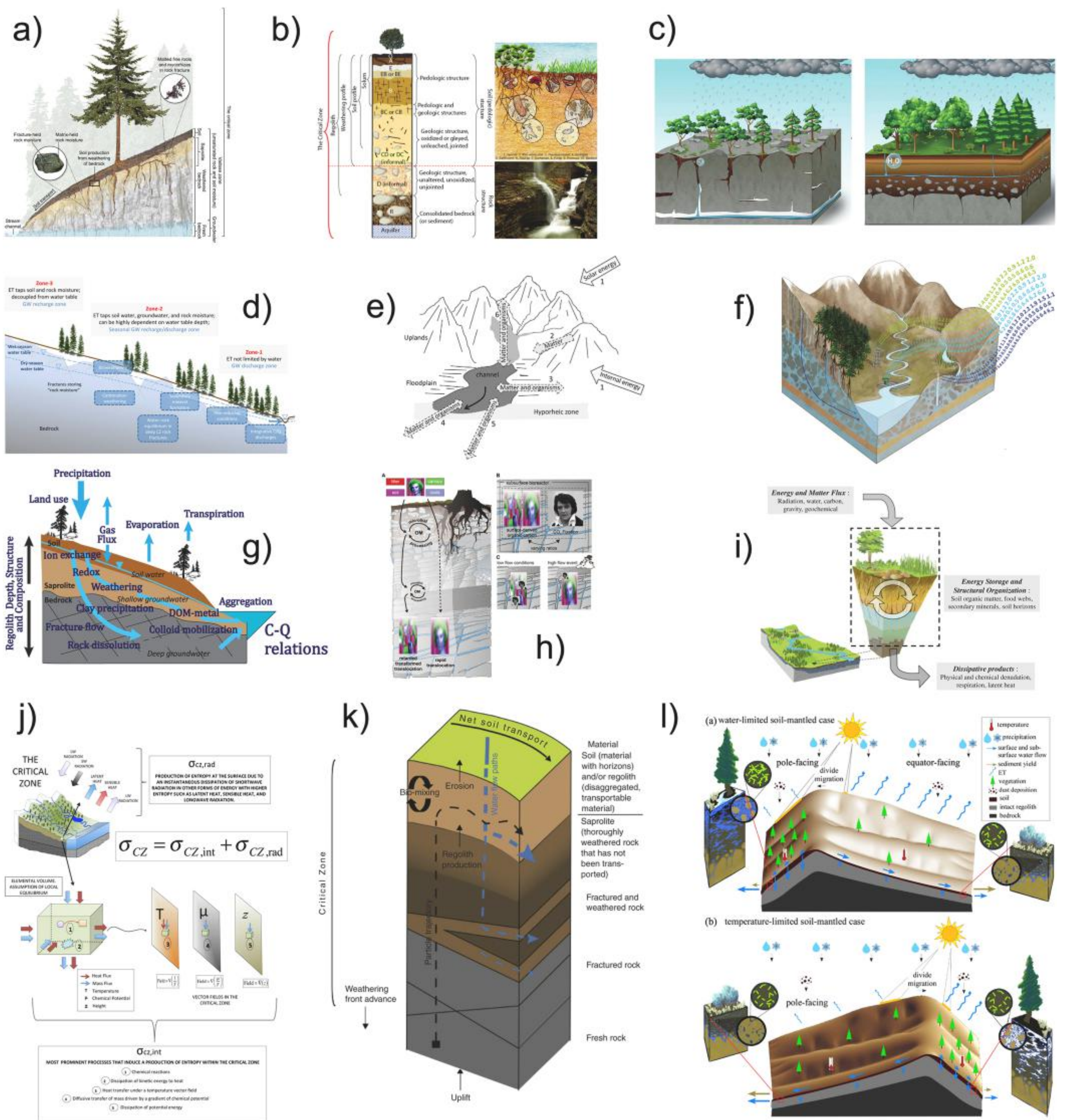

Fig. 5. Conceptual models of unifying threads defining the Critical Zone include: a) plants (Dawson et al., 2019 [Fig. 1]), b) soil (Lin, 2010 [Fig. 1]), c) bedrock (Jiang et al., 2020 [Fig. 1]), d) water (Brooks et al., 2015 [Fig. 3]), e) surface water (Wohl, 2015 [Fig. 9.1]), f) subsurface water (Singha and Navarre-Sitchler, 2021 [Fig. 1]), g) biogeochemical cycling of elements (e.g., nutrients, metals, or carbon; Chorover et al., 2017 [Fig. 1]), h) microorganisms (Kusel et al., 2016 [Fig. 4]), i) energy (Rasmussen et al., 2011 [Fig. 1]), j) entropy (e.g., thermodynamic and information; Quijano and Lin, 2014 [Fig. 2]), k) mineral weathering (Pope, 2015 [Fig. 4.1]), and l) measurement of slope aspect (Pelletier et al., 2018 [Fig. 4]).

energy, process, and measurement (Fig. 5). Additional proposals include the assemblage of human and more-than human processes and the potential of human activity to disrupt those processes (Fig. 6). Due to the spatial patchiness of the presence of the specific thread proposed, the CZ defined in this way often refers to (i.e., emphasizes) a collection of sub-planetary areas that are not contiguous (but may have planetary reach) and are changing constantly, depending on the availability and interpretation of data.

3.2.1. Material zones

A commonly proposed unifying thread is biota, such as plants (Fig. 5a; Dawson et al., 2019) or specifically trees (Brantley et al., 2017a). Plants, as opposed to animals, span the vertical dimension of the Critical Zone, connecting the lithosphere to the atmosphere. Plants build and plumb the CZ by altering the physical structure of the subsurface environment mechanically and chemically, and by cycling water, carbon, minerals, and nutrients. The area where plants live is dynamic due to the intermittent flow of ephemeral streams (Fovet et al., 2021), mobility of geochemical cycles (Arenes et al., 2018), or variability of human activity (Arenes et al., 2018), and researchers have called for investigating how the geographic distribution of plants affects soil moisture-driven processes across the CZ (Moore et al., 2015).

Other researchers argue that the CZ is defined not only by the biota but also by the abiotic material and energy flows that support it (Amundson et al., 2007). In the spectrum ranging from biotic to abiotic, soils are in the middle (Lin, 2014) and are therefore another commonly proposed thread (Fig. 5b; Richter, 2007; Lin, 2010; Banwart et al., 2011; Lin, 2014; Dixon, 2015; Giardino and Houser, 2015; Perdrial et al., 2015; Richter et al., 2015; Banwart et al., 2019; Aguilar et al., 2020). Soil includes all materials located above fresh, unweathered bedrock, making it the interface of the atmosphere, surface- and groundwater, and lithosphere. As such, it controls water flow, slope stability, and active chemical reactions, thus influencing how the CZ subsurface interacts with local materials everywhere (Perdrial et al., 2015).

Still others propose the unifying thread of the CZ to be the soil's base—the fresh bedrock from which soil is made—because it stores groundwater, supporting life above (Fig. 5c; Huang et al., 2021). By regulating the hydrologic properties of regolith, bedrock composition can play a fundamental role in vegetation growth, even on the order of climatic factors (Jiang et al., 2020). Deep water storage in unsaturated zone bedrock fractures can sustain transpiration for plants rooting into weathered bedrock long after shallow soils have dried. This deep transpiration occurs in forests (Rempe and Dietrich, 2018), agriculturally cultivated areas (Li et al., 2018a), and greenhouse experiments (Schwinning, 2020). Therefore, researchers call for an overarching conceptual model of lithologic phenomena, such as rock fracturing, weathering, damage, and reactions, to describe the CZ (Riebe et al., 2017).

3.2.2. Material cycles, information flows, and energy propagation

Other proposed unifying threads include what flows or cycles through the volume of the Critical Zone. Water is the primordial sustainer of life, facilitating important material and energy flows (Fig. 5d; Brooks et al., 2015; Giardino and Houser, 2015; Chorover et al., 2017; Wymore et al., 2017). It is water that travels from the atmosphere through the biosphere into the lithosphere to become stored as source water, soil water, and groundwater. Water is a crucial component in chemical weathering processes and the subsequent transport of dissolved and particulate material (Amundson et al., 2007; Banwart et al., 2011). Researchers call for investigating processes at the interfaces between the hydrological compartments (e.g., soil-atmosphere or soil-groundwater), which govern the age distribution of the water fluxes between these compartments and can greatly affect water travel times (Sprenger et al., 2019). The study of water paths across, rather than within, sites illuminates the water cycle and advances both hydrologic and CZ science (Brooks et al., 2015; Fan, 2015).

Within the hydrologic cycle, a proposed thread is surface water specifically (Fig. 5e). River systems constitute much less than 1% of freshwater in the CZ (Berner and Berner, 1987) but integrate diverse material and energy fluxes within and beyond the basin boundaries (Wohl, 2015). However, the proportion of the CZ thickness that is aboveground is only ~20%. In contrast, the proportion below ground is ~80% (Xu and Liu, 2017), so another proposed thread is groundwater (i.e., subsurface water) specifically (Fig. 5f). Groundwater is the largest reservoir of the three dynamically-linked branches of the water cycle (atmospheric, surface, and groundwater) and an active component of the hydrologic system (Leung et al., 2011). During periods of low precipitation, groundwater sustains streamflow, allowing access by deep vegetation, reacting with minerals to produce dissolved solutes and regolith, and influencing energy fluxes across the land-atmosphere interface (Fan, 2015; Wang and Zhan, 2015; Singha and Navarre-Sitchler, 2021).

Another proposed thread is the biogeochemical reactions in molecular-scale processes, which control productivity and contaminant cycling at larger scales. The thread may be defined as a mass by elements (e.g., nutrients, metals, or carbon) singly and in combination with others (Fig. 5 g; Richardson, 2017; Arenes et al., 2018; Dere et al., 2019). Some researchers investigate *C-Q* relations by measuring solute discharges down-gradient of reactive flow paths (Chorover et al., 2017). Models of *C-Q* relations explore theoretically how subsurface flow rate, flow pathline, and transit times control the weathering rate of the minerals in the CZ and, ultimately, the stream concentration of weathering products (Ameli et al., 2017). Controls on observed *C-Q* relations illuminate internal, integrated watershed function (the connections among hydrology, biogeochemistry, and landscape structure). Therefore, to describe the CZ, researchers call for an integrated model that combines process descriptions of biogeochemistry in terms of nutrient and carbon flows, reactive transport, and a simplified description of the soil food web (Banwart et al., 2012).

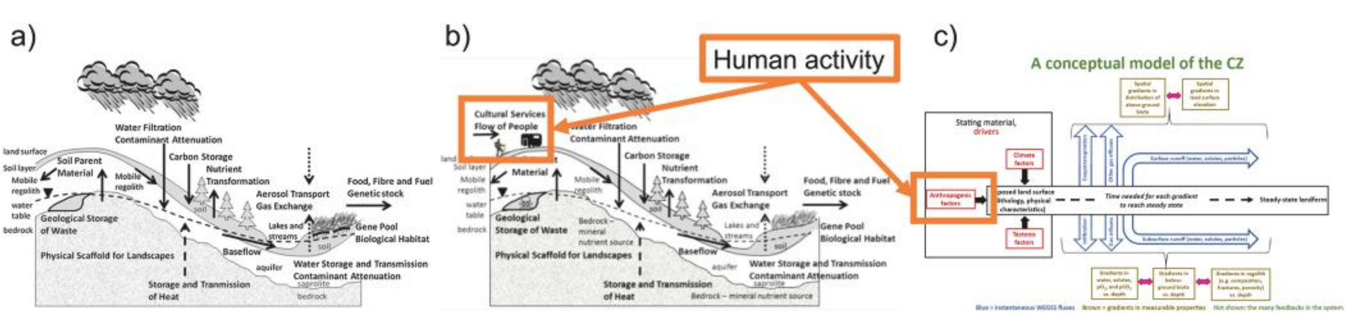

Fig. 6. Critical Zone researchers are increasingly focused on the resilience of the CZ to novel and large-scale anthropogenic perturbations (orange boxes added). a) A conceptual model of the CZ (Banwart et al., 2012 [Fig. 1]) is modified to incorporate the impact of human activity in b) Banwart et al. (2013) [Fig. 1]) at a surficial level. **c)** Human activity is conceptualized as a primary driver of CZ processes that affect CZ architecture, character, and dynamics (Brantley et al., 2016 [Fig. 1]).

Biogeochemical reactions involve electron transfers. Iron- and magnesium-bearing minerals and organic matter are key compounds interacting with each other and constituting necessary electron shuttles. Their solubility and structure control the mobility of many essential and toxic elements (Davranche et al., 2020). Microorganisms are the key players in electron transfer processes by acting as a catalyst between an electron donor and an acceptor, and through their contaminant detoxification metabolism (Fig. 5h). Therefore, elemental cycling is governed largely by microorganisms, specifically by the expression of their functional genes and translation into enzymes that catalyze geochemical reactions. Microorganisms are widespread across the CZ and can form hot spots with outsized influence on biogeochemical cycling (McClain et al., 2003), so researchers are interested in understanding how microorganisms and their genetic information are transported through the CZ (Kusel et al., 2016). As such, researchers call for increasing the integration of omics data in CZ research (Zhu et al., 2018).

Biological life, hydrologic flows, and biogeochemical cycling are driven by energy, which passes through the CZ freely (solar radiation) and through media (such as water, carbon, and physical/chemical denudation mass fluxes; Chorover et al., 2011; Rasmussen et al., 2011). Effective energy and mass transfers are connected to measurable properties of CZ structure and function (Fig. 5i). For example, on a global scale, the pattern of vegetation height is dominated by precipitation-related energy transfer (Xu and Liu, 2017). Defining the thread as energy is a way to quantitatively constrain and predict rates of CZ evolution. The use of such an integrated model of energy and mass flow through various subsystems of the CZ has the potential for incorporating biogeography and ecology (Minor et al., 2020). Other researchers analyzed concepts of thermodynamic and information entropy through the CZ (Fig. 5j; Quijano and Lin, 2014). Although the CZ has been defined as distinct from the atmosphere, the variability in climate can impact energy transfers to and through the CZ. In turn, the CZ and the associated interactions between the land and atmosphere (e.g., ecohydrology) feed back to play an essential role in Earth's climate system (Quiring et al., 2015).

3.2.3. *Processes and measurements*

Another proposed thread is a process, such as mineral weathering (Fig. 5k; Godderis and Brantley, 2013; Pope, 2015). The Weathering System Science Consortium was one of the first scientific collaborations inspired by the NRC's charge to study the Critical Zone. There was an ideal convergence of different disciplines—geomorphology, hydrology, pedology, mineralogy, petrology, geochemistry—around a common research goal. It was so successful that the consortium broadened its name to include the phrase "Critical Zone" (Critical Zone Exploration Network; CZEN), and the CZEN spread into other disciplines, such as ecology and geohydrology (Pope, 2015).

Other researchers propose that the thread is a single or a few measurements. For example, slope aspect is proposed to control major CZ processes (Fig. 5 l; Pelletier et al., 2018). This measurement can be unpacked as a conceptual model that demonstrates how broad-scale spatial variations in topographic asymmetry on hillslopes can be reproduced with only a few variables related to differential insolation (i.e., latitude and slope gradient), water availability (i.e., an aridity index), and mean annual surface temperature. This conceptual model shows that measurements of soil moisture and vegetation cover are essential for understanding landscape topography and CZ development across timescales. Similarly, other researchers show that measurements of the compound topographic index and potential evapotranspiration dominate the patterns of total CZ thickness, subsurface CZ thickness, and water table depth (Xu and Liu, 2017).

3.2.4. *Anthropogenic perturbations on the CZ*

Perhaps because of its strong hydrological heritage (e.g., notice the absence of human activity in the visual representations of the Critical Zone; Abbott et al., 2019), CZ often focuses on pristine landscapes with little direct human disturbance. Yet in the Anthropocene, humans act as a geologic force, moving more sediment than natural processes, such as hillslope failures, glaciers, and rivers (Hooke, 2000; Tarolli and Sofia, 2016). The worldwide deliberate shift of sediment by human activity has been estimated to exceed that of transport by rivers to the oceans by a factor of almost three (Price et al., 2011; Aguilar et al., 2020). Humans have modified and continue to modify most of the land cover of the CZ (Hooke et al., 2012) as well as land-atmosphere processes and climate (Pielke et al., 2011). Humans add elements to the CZ, changing nutrient and carbon cycles (Boyer et al., 2006), and with them whole terrestrial and freshwater ecosystems (Wohl et al., 2017). Some have declared that wilderness is dead—there will be more rather than less human manipulation of the CZ through time (Wohl, 2013). Therefore, another apparent unifying thread is the coupling of natural and managed ecosystems, the built environment, climatic forcing, and human activity (Amundson et al., 2007; Latour, 2014; Arenes et al., 2018).

Researchers increasingly point out that understanding the CZ properly entails predicting how it responds to anthropogenic perturbations (Amundson et al., 2007; Banwart et al., 2011; Giardino and Houser, 2015; Brantley et al., 2016; Richardson, 2017). Such a response is defined as a change in ecosystem function. This function is commonly measured at the ecosystem scale rather than at a spatially (e.g., hillslope) or hydrologically (e.g., watershed) defined scale precisely because an ecosystem is defined by its function (Tansley, 1935). Also, this function is commonly measured in terms of gross or net primary productivity, but has been measured in other ways, including the propagation of material and energy through all trophic levels (Lindeman, 1942; Odum, 1956; Megonigal et al., 2004), biogeochemical cycling (Hutchinson, 1948; Schlesinger and Bernhardt, 2013), soil formation (Chadwick et al., 1999; Richter et al., 2001; Vitousek, 2004), microbial processes (Firestone and Davidson, 1989; Billings and Tiemann, 2014), reaction kinetics (Lehmeier et al., 2013; Min et al., 2014), thermodynamics and conservation (Jorgensen and Svirezhev, 2004), resource management (Rockstrom et al., 2017), and agricultural output (Garbach et al., 2017).

Processes indicating gain or loss of ecosystem function are complex and interactive. Perturbations cause multiple effects that cascade through the CZ, so perturbations cannot be understood only in terms of a simple cause-and-effect paradigm, but rather with models of whole systems. The models should predict responses by showing how resilient or vulnerable a particular ecosystem is. This resilience can be conceptualized as the sum of resistance and recovery (Fuller et al., 2019), where resistance is the ability of the ecosystem to remain in its initial functional state during a perturbation, and recovery is the likelihood of its return after a perturbation. An ecosystem with low resistance can be pushed suddenly into a new state in which it functions differently or stops functioning entirely.

To understand the strength of a response, the time of recovery, and the overall resilience of ecosystems to novel and large-scale perturbations (these findings can then be summed across the CZ), researchers increasingly study the impacts of perturbations (e.g., land use) on the CZ in diverse biomes. At the Orgeval Critical Zone Observatory in France, the effect of intensive farming on chemical weathering was characterized by the chemical composition of different water bodies in two nested watersheds (Floury et al., 2018). At the Hainich CZO in Germany, connections were explored between surface conditions (in terms of water, biota, and biogeochemical functions), which were set by land cover and land management, and the subsurface (Kusel et al., 2016). At a CZO in the Loess Plateau of China, models were developed to describe soil water carrying capacity for the shallow soil layer, which was vegetated both naturally and anthropogenically (Shao et al., 2018). At the same CZO, bulk density was found to be an important factor that affected the variations in the soil water content in the deep soil layer (Qiao et al., 2018). At the Kabini CZO in India, impacts of climate and agricultural land use on water and biogeochemical cycles were studied together (Sekhar et al., 2016). Thus, human activity is increasingly represented in conceptual models of the CZ (Fig. 6; Banwart et al., 2013; Brantley et al., 2016).

4. Third-order meanings (anthropocenic): CZ as a vulnerable planetary home

Human activity is not limited to degrading the Critical Zone, but includes dwelling in it and locating human cultural life within it. The CZ is studied not only as a geophysical object, but as the place where we build our shelters (Lu et al., 2019; Luo et al., 2019), grow our food (Richter, 2007; Yoder et al., 2021), extract our minerals (Smith et al., 2016; Zhang et al., 2019a), educate our children (Wymore et al., 2017; Dere et al., 2018), govern our societies (Latour, 2014; Montanarella and Panagos, 2015), run our economies (Field et al., 2014; Richardson and Kumar, 2017), and leave our legacies (Edgeworth, 2018).

This more robust meaning of human activity was actually imbued in the CZ at its conception, when the NRC stated that CZ science and Earth science share a motivation to help maintain current and future human habitability on Earth (NRC 2001). The association between CZ and habitability is etymologically appropriate. Habitability is the functionality of biotic and abiotic resources and relationships supporting the survival and reproduction of living organisms. While *habitat* is generally used in a species- or organism-specific way (Krausman and Morrison, 2016), *habitability* is applicable up to the planetary scale and oriented solely towards Earth, the greater "habitat" for the entire biosphere. Furthermore, the word "zone" derives from the Greek *ζώνη/zōnē* (originally "belt"), used by Parmenides and Aristotle in a proto-Earth science manner to divide the Earth by latitude into a few geographic bands ("zones") with emphasis on the zones that are habitable (*οἰκήσιμος*/oikēsimos; Aristotle, 1987; Strabo, 1997).

CZ researchers repurposed this ancient connection, intuitively or accidentally. In CZ, the ancient Parmenidean-Aristotelian geographic *ζώνη* is transformed from a few bands encircling the Earth to the single-layer comprising much of the planet's surface and subsurface, even as the salience of habitability in the term is preserved. The adjective "critical" in CZ specifies the concern with habitability because implied in "critical" is the importance of attending to the CZ precisely so that it remains habitable (NRC 2001; Richardson, 2017; Gaillardet et al., 2018; Luo et al., 2019). Other senses of "critical" ("critical systems" in software engineering; "a patient in critical condition" in medicine) call attention to the alarming possibility that CZ functionality could become stressed to failure (Latour, 2014).

CZ research requires an orientation towards process and function beyond basic structural dimensions (Connor et al., 2015), and implies a human motivation to care about, study, and protect the CZ. Some argue that sustainability of the CZ (including human society in it) depends on international CZOs in particular and CZ science in general (Zhang et al., 2019b). Others add that opening up channels for dialogue among the geosciences with the social sciences and humanities can help foster the necessary care for the CZ as the place we come from and not just live on (Latour and Weibel, 2020; Mahony, 2022).

We propose that the human motivation to care about the CZ gives CZ an additional meaning of "home". The connection of CZ science to value-laden conceptions of home was heralded in older terminology of ecology and ecosystems that preceded ideas like CZ and the Anthropocene. The prefix "eco-" stems from *οἶκος/oikos*, the Greek word for "home," "household," or "dwelling-place" that was adapted by the ancients to identify the habitability (*οἰκήσιμος*/oikēsimos) of a geographical "zone" as cited above. While habitability is value-neutral, home is value-laden, carrying powerful associations of the "nurturing shelter". "given over to the hidden processes of life"… "devoted to the sustenance of the body," where "we feed, wash, and rest," and where "life begins and ends" (Tuan, 1975). Ethnographers have proposed such a shift from seeing the CZ as sites located in the geographic grid to a representation of meaningful events occurring in our home (Arenes et al., 2018; Arenes, 2021), in a nearly sacred place needing to be sustained because it sustains us. As such, this (third-order) meaning brings literal pride of place to CZ research, building upon the first- and second-order meanings of spatial reference and geophysical data.

4.1. Human activity at home

Critical Zone recalls the biogeochemical description of a planet comprised of nearly concentric spheres (i.e., the geosphere, lithosphere, hydrosphere, biosphere, atmosphere, and others; Shoshitaishvili, 2021). Soon after the introduction of the idea and term "biosphere," scientists and philosophers proposed an additional term to designate the human-adapted layer covering the Earth's surface: the "noosphere," or sphere of human symbolic thought and its products (Vernadsky, 1945; Pitt and Samson, 2012; Teilhard de Chardin, 2015). Vernadsky and his interpreters suggested that Earth science should inform the "co-evolution of the biosphere and noosphere" (Moiseev, 1993). The biosphere and noosphere were presented as analytically distinct, but in practice were treated as a coupled dynamic unity for human societies to help maintain.

Some CZ discussions aim to further narrow the analytic distinction between the human and the more-than-human. One approach outlines a potential "intellectual ecotone" of environmental humanities, religion, and ecology. The CZ is argued to be ***a planetary animist sphere*** based on the livingness of Earth as a union of biotic (human and more-than-human) and abiotic worlds. The CZ as a place of "interplay between biotic and abiotic components of the planet" (Amundson et al., 2007) is redefined more specifically as "the affective effects of the entwinement of organic beings and inorganic earth materials, such as within human and animal bodies" (Yu, 2020). In this new animism, the livingness of Earth is expressed in biochemical, sentient, and affective terms to underpin a planetary environmental consciousness documented with an "ethographical" approach (van Dooren and Rose, 2016). The livingness of Earth has also been expressed as intelligence, which impacts the form and function of the CZ (Frank et al., 2022). Such visions of a thoroughly interwoven human and biospheric CZ recall Gaia theory, where Earth processes and all living things are seen as constituting a single, expansive living system maintaining through homeostatic mechanisms the conditions for its persistence (Lovelock and Margulis, 1974). In particular, the phrase "Gaia's skin" (Lovelock, 1991) anticipated a key aspect of the CZ, connecting a spatial demarcation of Earth's surface with the sense of vulnerability and motivation to care for the more-than-human.

Other "-sphere" terms have since been introduced to designate Earth-spanning zones characterized by collective human activity and impact: the "anthroposphere," "technosphere," "infosphere," and "archaeosphere". Some of this human activity is projected to be beneficial for society at a minimal cost to the CZ. For example, the technosphere is the portion of the human CZ that sustains many contemporary forms of human life. It includes active urban, agricultural, and marine components, and has been estimated to have a mass of approximately 30 trillion tons, supporting a human biomass that is ~5 orders of magnitude smaller (Zalasiewicz et al., 2017). Meanwhile, the infosphere (Toffler, 1980; Floridi, 1999) houses human knowledge and communication on various media, some of which require relatively few physical resources to develop and access (e.g., digital media). This asymmetry between the technosphere and infosphere suggests that our planetary cultural home could unfold with less cost to the CZ because the media-flexibility of the infosphere can afford opportunities to enrich human experience and communication without significant expansions to the technosphere's material and energy use.

4.2. Protecting home

Some researchers argue that Critical Zone science has not yet incorporated the CZ's criticality for sustaining the well-being of human society (Lu et al., 2017). Although the integration of cultural norms with the concept of the (smaller-scale) ecosystem has been proposed (Chapin et al., 2010), the (larger-scale) Critical Zone Observatory network in the

US does not engage social science, thus limiting hypotheses about the human social aspects of the CZ (Brantley et al., 2017b). However, the multilayer scalable framework of CZ provides points of intervention on both the local and global scale, which can encourage local and international political action to impact the natural environment and citizens simultaneously (Latour, 2014). For example, CZ science can help researchers understand ecosystem services of soil, informing the quantitative monetary valuation of soil within its full life cycle, then informing policy (Banwart et al., 2011, 2012). Some consider CZ science a good match with the European Union's policy strategy to protect soil (Montanarella and Panagos, 2015) because CZ science enlarges the scope of study beyond the original use of soil for agricultural purposes (Richter, 2007), allowing soil health to be measured appropriately (Yoder et al., 2021).

Thus, CZ science and the concept of ecosystem services have combined into CZ services (Fig. 7). This concept embraces a more extensive context, spatially and temporally, to determine the constraints that limit the provision of services, and offers a potentially powerful currency for evaluating whole systems in the CZ (Field et al., 2014). It allows assessment of human impact on the CZ with both short- and long-timescale processes accounted for (Richardson and Kumar, 2017). In this way, the CZ is studied as places defined by political and economic, rather than geophysical, boundaries.

However, evaluating the importance of CZ services when ecological processes are linked to societal benefits through market and nonmarket valuation presents a major challenge. One suggestion to integrate CZ services into an evaluation currency is by quantifying the energy flux available to do thermodynamic work on the CZ (Field et al., 2014). In a more explicit and rigorous definition of CZ services, the economic value of services provided by the atmosphere and shallow lithosphere was added to the more commonly accounted aboveground services related to vegetation and surface waters (Nie et al., 2021). These research directions in economics and policy address problems bearing directly on societal interests, as initially envisioned at the introduction of the CZ concept (NRC 2001; Giardino and Houser, 2015; Richardson, 2017).

5. Emerging trends in CZ research

The flexibility of the Critical Zone concept has helped make the CZ endeavor fruitful. To continue this trajectory, researchers advocate a denser network of Critical Zone Observatories and a fuller library of CZ models and databases (Guo and Lin, 2016). Here, we identify emerging trends that begin to meet these needs by redefining the CZO so that spatiotemporal scales are both expanded and compressed, and by coupling research from various disciplines. These trends characterize the CZ by its geological, biological, ecological, and atmospheric features along with human and socioeconomic factors, thus harmonizing the three tiers of meanings of CZ analyzed above, and advancing new directions in CZ research and new meanings of the CZ itself.

The US CZO program has been limited to nine locations. As such, there were no CZOs in periglacial (Rowley et al., 2015; Wymore et al., 2017), coastal, or estuarine (Liu et al., 2021) settings. Their inclusion into the CZO network has been argued for due to their susceptibility to climate change and their provision of ecosystem services. Also, there were no CZOs in urban areas, and their inclusion has been argued for due to needs to sustain human habitability where the densest populations are (Brantley et al., 2017b; Wymore et al., 2017; Lu et al., 2019). In response to these needs, the US CZO program was succeeded by the Critical Zone Collaborative Network (CZCN) in 2020 (Leon et al., 2019). The CZCN officially expanded the network of observatories (now called "field sites") to almost every country in the CZ by changing to a bottom-up consortium model that invites participation from existing research networks and individual researchers, similar to the description above in Section 3.1.4. The CZCN also initiated the building of computational infrastructure to merge previously-collected data sets from the original nine CZOs with new data sets (Leon et al., 2019) and to ensure that new data sets meet FAIR data reuse principles (Horsburgh et al., 2021). One of the first sites to be added is Sleepers River, VA, which is a USGS research watershed. Here, new research tests hypotheses to disentangle complex CZ processes that drive stream DOC, and researchers found that stream chemistry mirrors the less-monitored subsurface water chemistry (Stewart et al., 2022).

Modern CZOs represent the heterogeneity of the CZ better (Fig. 8). For example, researchers reconceptualized the CZO by putting the layers that are critical for life on Earth in the center of the conceptual model instead of out at the perimeter, where they are minimized as a "thin skin" (Arenes, 2018; Fig. 8a). Only the cycles relevant to the site are represented, so every site results in a unique conceptual model. Furthermore, researchers are simulating CZOs in computational space-time. For example, researchers developed a serious immersive Virtual Reality game ("CZ Investigator") set in the Shale Hills CZO, enabling users to have an accessible learning experience with the CZ and creating awareness of CZOs on a societal level (Sajjadi et al., 2020; Fig. 8b).

Beyond Earth, CZ provides a platform to guide astronomers and planetary scientists in their study of distant planets and asteroids whose global and astronomical conditions could theoretically sustain biospheres (Lin, 2005, 2010; Ashley, 2020). Proto-CZs (abiotic CZs) that support organic chemistry have already been recognized (European Space Agency, 2019). Mars is a suitable near-term target to study past habitability or preservation of prebiotic chemistry in our solar system based on active research already taking place on/of the planet. The last few decades of research have led to significant discoveries about the Martian atmosphere and surface, so discussion of potential CZs on Mars (and other desert planets) in the form of "inverted" CZs has already begun (Boston, 2015). Researchers are beginning to explore the subsurface, guided by system-science concepts from CZ science (Fackrell et al., 2020; Fig. 8c, f). Specifically, identification of CZ(s) on Mars is already feasible at Gale Crater (Li et al., 2015).

Modern CZOs also capture the temporal dynamism of CZ evolution better (Fig. 9). Geologic history (as recorded in the CZ) can provide scientific evidence and decision support regarding future changes to the CZ. In the southern Italian Alps, researchers chronicled glacial erosion over the last 2000 years and produced evidence that human activities were the dominant forcing factor of erosion since the late Roman Period (Rapuc et al., 2021). Prehistoric records (e.g., major volcanic episodes, meteorite impacts, and other extreme events) in the more ancient past (e.g., during the Quaternary Period) have been conceptualized as "Paleo-CZs". This is a powerful tool for understanding the response of the CZ to large-scale events, such as glaciations and sea-level fluctuations (Fig. 9a; Ashley, 2020). Looking forward, time scales are compressed to hyper-focus on current human activity and its impact on the CZ (White et al., 2015). Alternatively, focus is put on multiple and widely disparate timescales to capture interactions of geochemical, geomorphological, hydrological, and biological processes together with human activity. For example, at the Susquehanna Shale Hills CZO, multiple isotope proxies (termed "CZ-tope") are applied on the same location to capture phenomena across daily to millennial time scales (Fig. 9b; Sullivan et al., 2016). This research characterizes CZ evolution in terms of temporally nested reaction fronts over millennia.

While CZ science focuses largely on structures, processes, and mechanisms, some researchers argue that more progress can be made on functions (Guo and Lin, 2016), primarily in areas of active land use. There is an emerging trend to couple CZ science with "multi-functional landscape" research to meet sustainable development challenges from local to global scales (Fig. 10; Chamorro et al., 2015; Luo et al., 2019). The CZ is classified by the capacity of the landscape to provide goods and services for human well-being, directly or indirectly (Fig. 10c; Lu et al., 2017; Lu et al., 2019). Such research on landscape multi-functionality is widely recognized as a significant basis for sustainable land development (de Groot, 2006; Lovell and Johnston, 2009).

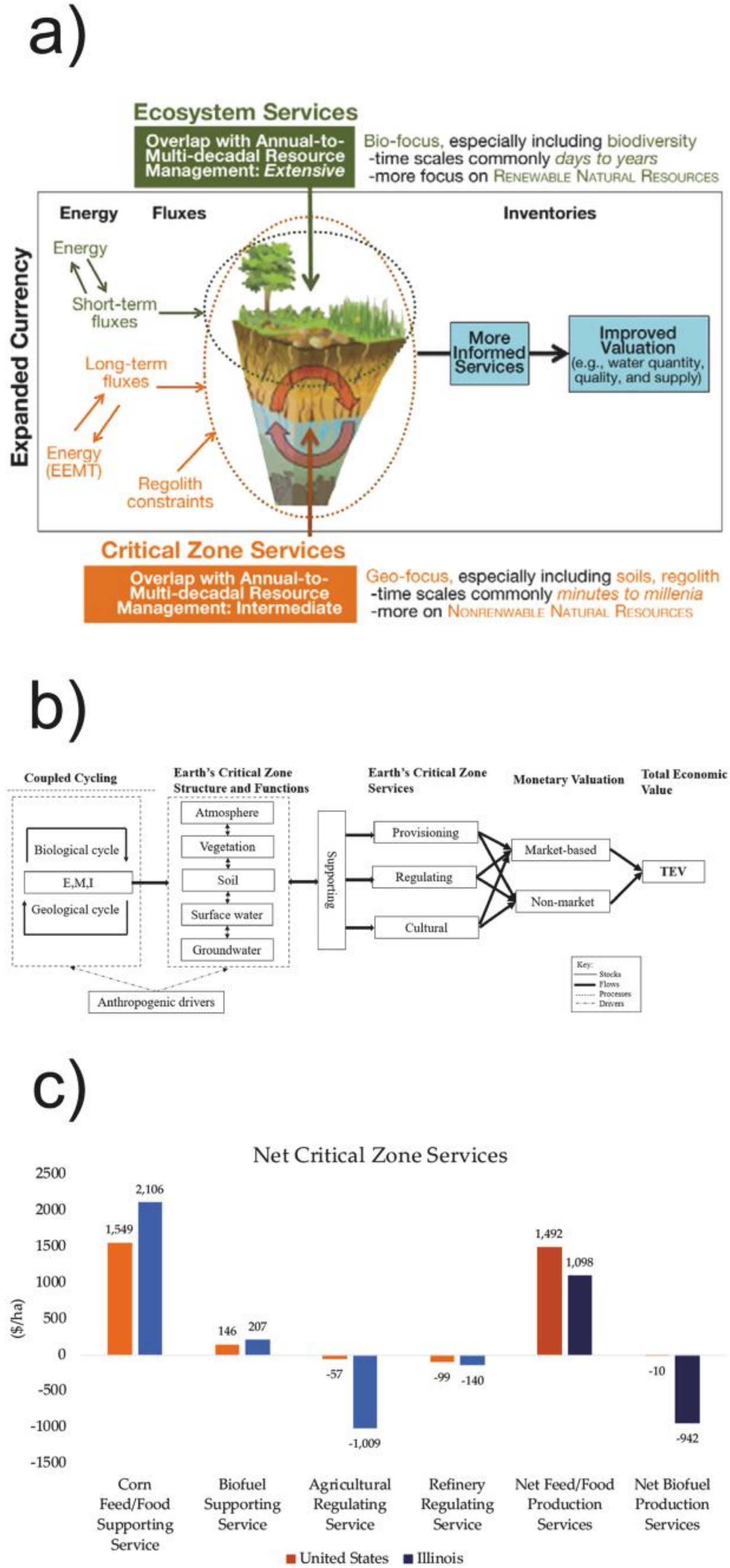

Fig. 7. a) Ecosystem services are adapted to be understood as Critical Zone services (Field et al., 2014 [Fig. 1]). b) Proposed framework for economic valuation of the CZ (Nie et al., 2021 [Fig. 2]). c) An example of the breakdown of CZ services ($/ha) for the US and Illinois (Richardson and Kumar, 2017 [Fig. 10]).

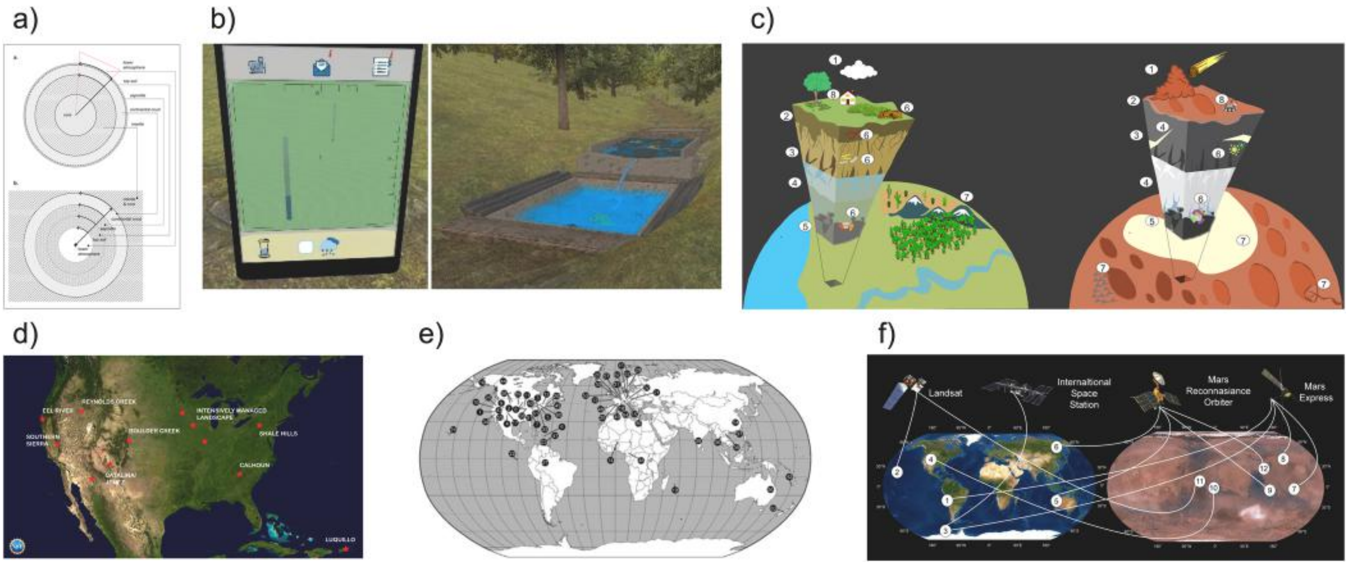

Fig. 8. Emerging trends in Critical Zone research with respect to spatial scale include: a) reconceptualizations of the Critical Zone Observatory (e.g., Arenes et al., 2018 [Fig. 3]), b) study of the CZO in computational spacetime (Sajjadi et al., 2020 [Fig. 5]), and c) study of the CZ on exoplanets (e.g., Mars; Fackrell et al., 2020 [Fig. 1]). The expansion of the CZO network is shown with d) map of the original CZOs across the US (Brantley et al., 2017b [Fig. 2], e) map of CZOs across the world (Giardino and Houser, 2015 [Fig. 1.2]), and f) map of proposed CZOs across Mars (Fackrell et al., 2020; [Fig. 2]).

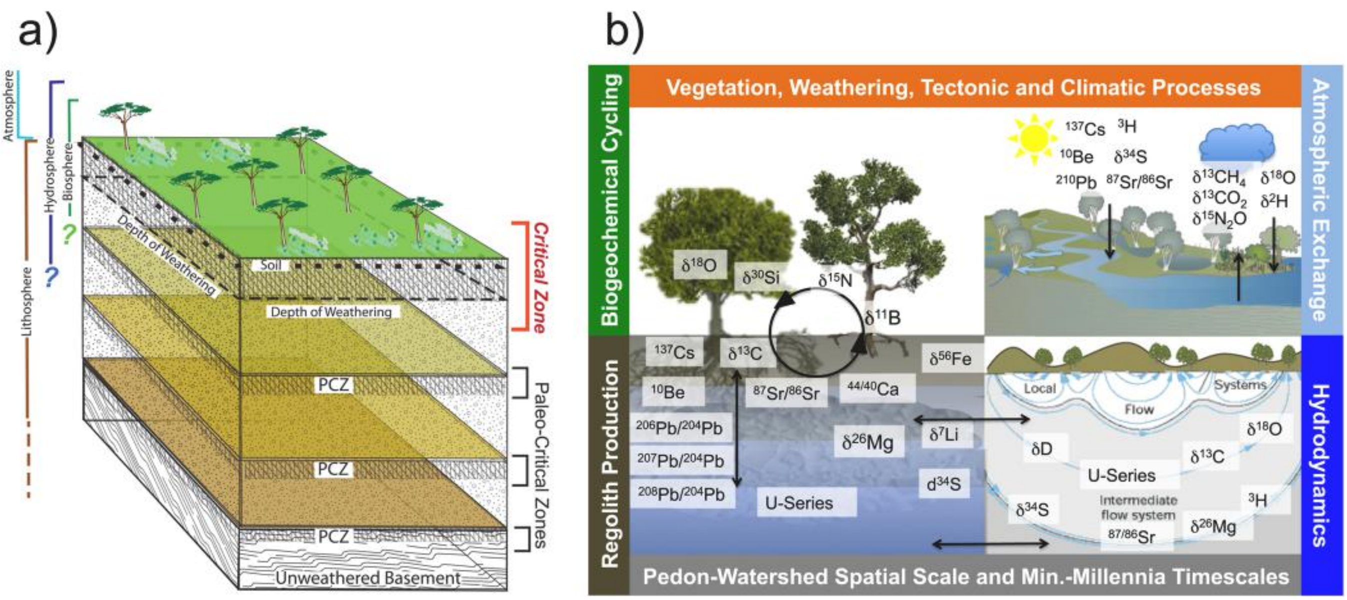

Fig. 9. Emerging trends in Critical Zone research with respect to time scale include: a) expansion of time scales in history to establish "Paleo CZs" (Ashley, 2020 [Fig. 3]), and b) the combination of widely disparate timescales (Sullivan et al., 2016 [Fig. 1]).

6. Conclusion

Elements of Critical Zone science were anticipated over a century ago. General Systems Theory laid the modern groundwork by breaking down systems into their ontology, systems epistemology, and values (von Bertalanffy, 1950, 1951, 1968) but remained non-specific. Concepts like the biosphere (Suess, 1875), ecosphere (Cole, 1958), and Gaia (1974) referred to the global ecosystem with overlap among them, causing considerable confusion (Huggett, 1999). Then the concept of the Critical Zone was introduced (NRC 2001). It shares elements with its precursors and has developed its own polysemy, which has brought both promise and confusion. We hope to have clarified some of this confusion by organizing extant meanings of CZ in a conceptual scaffold that distinguishes the ontological, epistemic, and anthropocenic. Specifically, the epistemic and anthropocenic meanings have given the CZ an added value beyond precursor terms, which remain primarily ontological (spatial). This value appears to be borne out in the literature, as many researchers adopt a CZ approach (Vero et al., 2018; Fackrell et al., 2020; Liu et al., 2021), framework (White et al., 2015), lens (Aguilar et al., 2020; Yoder et al., 2021), paradigm (Richardson, 2017), or perspective (Field et al., 2014; Dawson et al., 2019; Zhang et al., 2019b).

In this review, we emphasize that the CZ concept actually reorients space by drawing attention to Earth's most critical ecosystem functions (Latour, 2014). This occurs because the epistemic and anthropocenic meanings are dynamic and adaptive to scientific and societal needs. Epistemic and anthropocenic meanings inform the model of the Critical Zone Observatories, which support innovative collaborations between scientific and technological communities by evolving in tandem with the

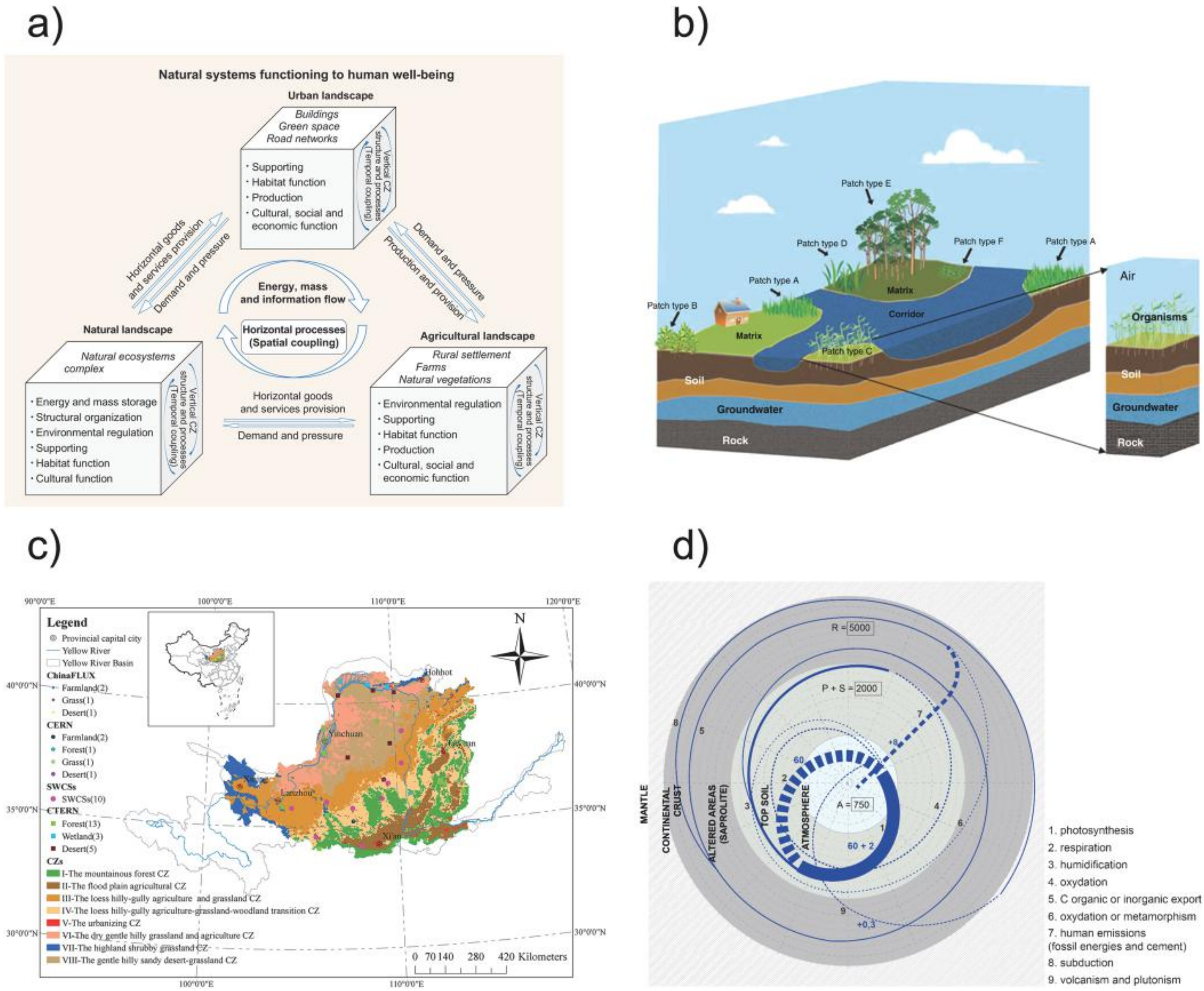

Fig. 10. Emerging trends in Critical Zone research with respect to coupling of research disciplines include: a) new conceptual models connecting the urban and agricultural landscapes to the natural landscape (e.g., Luo et al., 2019 [Fig. 1]), b) new conceptual models accounting for functional patchiness and heterogeneity in the landscape (e.g., Chamorro et al., 2015 [Fig. 7.9]), c) new maps drawn at the regional scale accounting for functional patchiness and heterogeneity in the landscape (Lu et al., 2019 [Fig. 2]), d) new conceptual models of elemental flow through the CZ accounting for human activity (e.g., carbon cycling; Arenes, 2021 [Fig. 12]).

physical CZ (Giardino and Houser, 2015; Brantley et al., 2017b; Fackrell et al., 2020). When new information causes a change in one tier of meanings, the other tiers must be revisited and possibly revised. In a hypothetical example, if human activity were discovered to affect a particular area of Earth, such as the sub-pedosphere portion of the lithosphere, with potentially deleterious consequences for life and human societies, then the spatial (ontological) CZ should expand to include the sub-pedosphere because human impact (anthropocenic) as well as human knowledge (epistemic) of our impact had expanded to include this portion of the planet.

It is important to note a potential contemporary source of confusion revealed by our conceptual scaffold. We consider the epistemic and anthropocenic CZs mutable, whereas the ontological CZ has so far been fixed as canon (i.e., the crust of the entire planet, not including oceans; NRC 2001). Therefore, it is possible that current epistemic or anthropocenic meanings have expanded the CZ beyond the boundaries set by its original ontological meaning, and the three tiers no longer resonate but conflict. In a more concrete example, the boundaries between continents, oceans, and the atmosphere are increasingly permeable as permanent human activity grows in areas outside the canonical CZ. As a backdrop, the interface between oceans and the atmosphere controls climate on the continent, which is of crucial importance (Byrne and O'Gorman, 2018). There is a constant presence of sailors, fishermen, oil drillers, cargo transporters, and commercial passengers, all transporting materials and goods across the ocean (Jouffray et al., 2020). Projections suggest increasing quantities of oceanic life will be harvested from the ocean for food (Jouffray et al., 2020), carbon can be sequestered in the ocean floor (Teng and Zhang, 2018), and aeolian dust will deposit more continental material (biological and mineral) around the world (Rodriguez-Caballero et al., 2022). If the ontological boundaries of the CZ are redrawn to include the oceans and atmosphere, then mass flux and mass balance calculations could be improved to increase the understanding of geophysical processes worldwide, thus helping better meet the aims for which the NRC coined the CZ.

The CZ concept has a unique provenance and semantic structure. Our review suggests that it is precisely this uniqueness that continues to help researchers across disciplines work together to develop an engaged understanding of our place, and life's place, on this planet in the

Anthropocene.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ancene.2023.100377.

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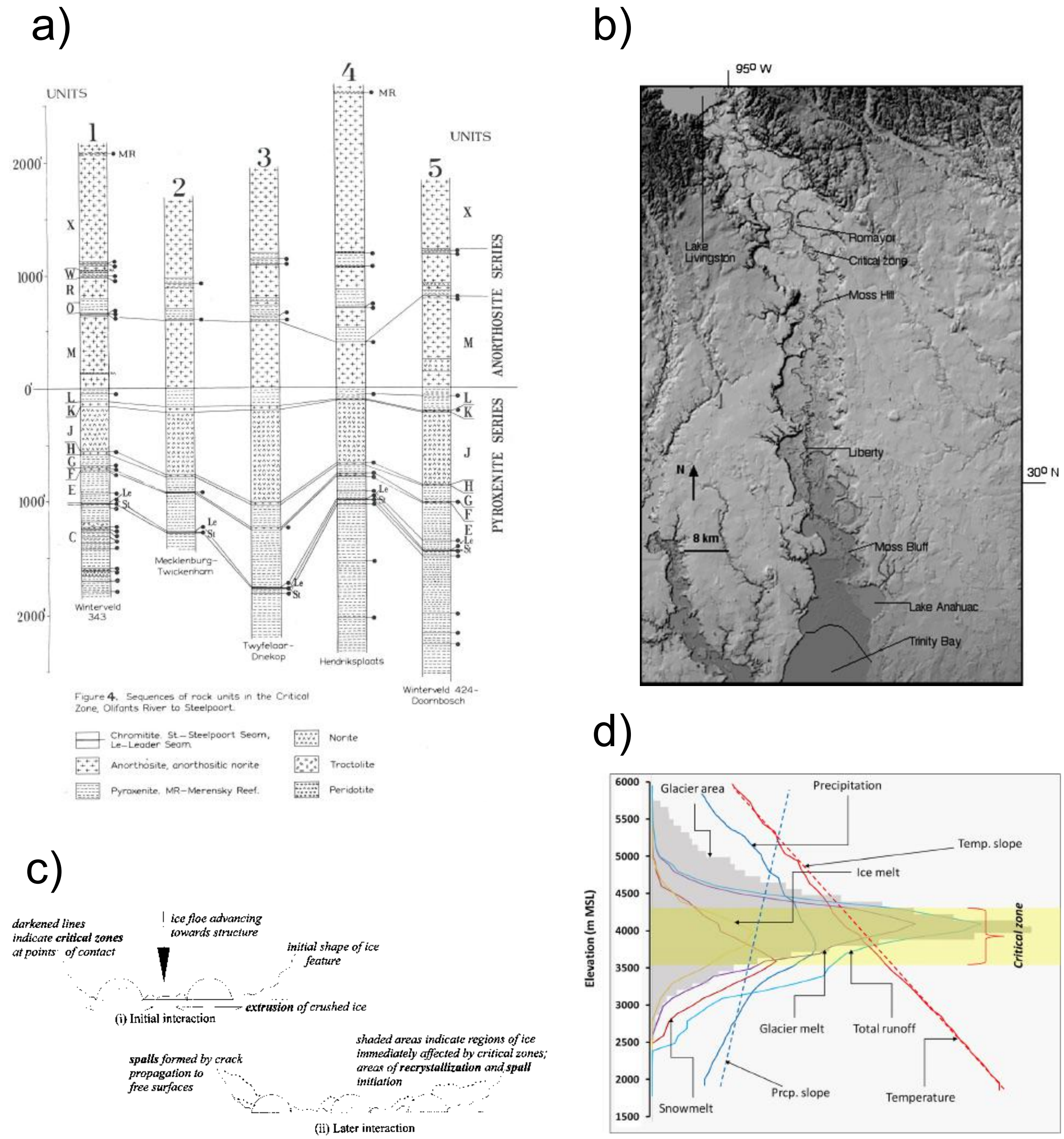

Supplementary Figure 1. Different meanings of Critical Zone in various geoscientific disciplines. **a)** In petrology, CZ demarcates the section of highly differentiated rocks from a horizon just below the lowest chromite seam to the base of the Main Norite Zone, which is located in an igneous geological formation [Bushveld Complex] in South Africa (Kuschke 1940; Cameron 1963 [Fig. 4]). Deposits of precious metals (e.g., platinum and gold) in the CZ can be mined, making it one of the world's most intensely researched geological entities (Wilhelm et al. 1997). Quantitative models of how the transition formed at the boundaries of this CZ are still being researched (Boorman et al. 2004). **b)** In river hydrology, CZ demarcates geomorphological transitions in river channels, which are important hinge points and indicators of change in dominant hydrologic processes and ecological characteristics (Phillips and Slattery

2008 [Fig. 1]). **c)** In glaciology, CZ demarcates local regions of ice where high pressures occur over short periods, leading to ice crushing and extrusion (Johnston et al. 1998 [Fig. 2]). **d)** In alpine hydrology, CZ demarcates the elevation of the mountain slope where temperatures, snow cover, and the fraction of basin area are high; limited by energy and snow equally; and dominate snowmelt volumes during peak discharge events (Biggs and Whitaker 2012; Shafeeque et al. 2019 [Fig. 1]).

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