Critical Zone Science in the Anthropocene: Opportunities for Biogeographic and Ecological Theory and Praxis to Drive Earth Science Integration

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ABSTRACT

Critical Zone Science (CZS) represents a powerful confluence of research agendas, tools, and techniques for examining the complex interactions between biotic and abiotic factors located at the interface of the Earth's surface and shallow subsurface. Earth's Critical Zone houses and sustains terrestrial life, and its interacting subsystems drive macroecological patterns and processes at a variety of spatial scales. Despite the analytical power of CZS to understand and characterize complicated rate-dependent processes, CZS has done less to capture the effects of disturbance and anthropogenic influences on Critical Zone processes, although some Critical Zone Observatories (CZOs) focus on disturbance and regeneration. Methodological approaches from biogeography and ecology show promise for providing Critical Zone researchers with tools for incorporating the effects of ecological and anthropogenic disturbance into fine-grained studies of important Earth processes. Similarly, mechanistic insights from CZS can inform biogeographical and ecological interpretations of pattern and process that operate over extensive spatial and temporal scales. In this paper, we illustrate the potential for productive nexus opportunities between CZS, biogeography, and ecology through use of an integrated model of energy and mass flow through various subsystems of the Earth's Critical Zone. As human-induced effects on biotic and abiotic components of global ecosystems accelerate in the Anthropocene, we argue that the long temporal and broad spatial scales traditionally studied in biogeography can be constructively combined with the quantifiable processes of energy and mass transfer through the Critical Zone to answer pressing questions about future trajectories of land cover change, post-disturbance recovery, climate change impacts, and urban hydrology and ecology.

INTRODUCTION

New and dynamic biogeographical patterns are a characteristic feature of the Anthropocene, the current epoch defined by intense human influences on Earth systems, because of humanity's large-scale and unprecedented effects on terrestrial and atmospheric systems (Allen et al., 2015; Ramanathan and Barnett, 2003; Revelle and Suess, 1957). As anthropogenic impacts increase in magnitude and scale, fundamental biogeographical processes that create and sustain ecosystem patterns will continue to change at an unprecedented rate. This is especially true in Earth's Critical Zone, which is defined as the "permeable near-surface layer…from the tops of the trees to the bottom of the groundwater" (Critical Zone Observatories). Biogeography, ecology, and Critical Zone Science (CZS) are uniquely situated to document anthropogenic change because these fields intentionally operate at multiple spatial and temporal scales and all are concerned with the intersection of abiotic (atmosphere, hydrosphere, cryosphere, and lithosphere) and biotic (biosphere) processes. Leveraging differences in expertise and philosophy between these related fields creates an opportunity to develop synergistically our approach to understanding Earth system organization, processes, and patterns. Integrating the spatialized ecology of biogeography and the potentially unique responses of individual species and communities to disturbance with enhanced knowledge of Critical Zone rates and fluxes provides new opportunities to interpolate CZS across larger scales and to explain observed changes in the Anthropocene. At the same time, insights from CZS, including hydraulic flow paths and subsurface patterns of geomorphology, can inform understandings of major spatio-temporal patterns and variances identified and studied in the near-surface and aboveground by ecology and biogeography (Moore et al., 2015). To aid in this synergy, the recent development of an integrating Critical Zone model fills an existing gap in biogeographic theory (Rasmussen et al., 2015).

Synchronous and widespread changes in global climate and land cover across wild and managed landscapes underscore the urgency for this integrated science approach (Stocker, 2014). Expanding global human populations and the accelerating intensification of resource use have produced dramatic and measurable effects on biotic and abiotic systems and processes. Since its introduction into the scientific literature, the “Anthropocene” concept (Crutzen and Ramanathan, 2000; Falkowski et al., 2000), of a “human-dominated biosphere” (Nyström and Folke, 2001), has gained currency across a breadth of disciplines within natural and physical sciences, social sciences, and humanities as a way to describe this epoch of intense human influence. A number of definitions have been advanced, many of which reflect paradigms and epistemologies of particular disciplines. Generally, the Anthropocene has been established as a period encompassing the present and some component of the recent past that is marked by significant and measurable anthropogenic disturbance and an accelerating transformation of the biosphere into anthromes, novel ecosystems, and various other socionatural hybrids (Ellis, 2015). While precise initiation date(s) of the Anthropocene are difficult to determine and may reflect regional spatial and temporal asynchrony (Edgeworth et al., 2015; Waters et al., 2016), the diverse and dramatic impacts of humans on global systems (*e.g.,* global climate change, stratospheric ozone depletion, fire suppression, deforestation, land cover change, urbanization, and many others) provide strong evidence for a new geologic epoch (Steffen et al., 2016; Brown et al., 2017).

The impacts of contemporary humans are evident planet-wide, echo across trophic scales, and are reflected in species distributions and abundances. Humans alter atmospheric chemistry and composition, land and sea temperatures, and the cycling of energy and nutrients at global scales, and humans introduce contaminants to terrestrial, aquatic, and atmospheric systems. Scientific engagement with the Anthropocene requires understanding that humans are agents capable of altering the rates, fluxes, and processes occurring within the Critical Zone across spatial and temporal scales. Scientific explanation and understanding of the impacts of the Anthropocene requires research into the rates, fluxes, and cycles of energy and matter through coupled terrestrial, hydrological, and atmospheric systems, and the ways in which human influences combine with naturally occurring phenomena to alter these rates, fluxes, and cycles beyond the historical range of variability. Here, we present Critical Zone Science – an evolving Earth Science that has been established largely at the nexus of geosciences and hydrology – and describe its focus and limitations. We describe the theoretical orientations that inform research in CZS and biogeography, arguing that a particular theoretical and methodological position provides the best opportunity for addressing and understanding Anthropocene impacts on the Critical Zone. We then present a model of Critical Zone fluxes of energy and materials to demonstrate the utility of integrating biogeographical understandings of disturbance with studies of the Critical Zone to understand rapid change across spatial and temporal scales ('hot spots' and 'hot moments'). We follow with a discussion of how particular disturbances can affect fluxes of matter and energy within and through the Critical Zone. We end with a call for synergy between biogeographic and Critical Zone research that we believe can productively explain ecosystem pattern and process in ways unavailable to each discipline independently. This synthesis, we argue, provides the best opportunity for understanding biotic and abiotic changes that define and characterize the Anthropocene.

2. Science in the Critical Zone

2.1 A New Science for the Anthropocene

Critical Zone Science was first defined by the National Research Council (NRC) in the 2001 document *Basic Research Opportunities in Earth Science*. The NRC report describes the Critical Zone as "the heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources." The NRC directly acknowledges human impacts upon terrestrial ecosystems:

> The rapidly expanding needs of society give special urgency to understanding the processes that operate within this Critical Zone. Population growth and industrialization are putting pressure on the development and sustainability of natural resources such as soil, water, and energy. Human activities are increasing the inventory of toxins in the air, water, and land, and are driving changes in climate and the associated water cycle. An increasing portion of the population is at risk from landslides, flooding, coastal erosion, and other natural hazards. (National Research Council, 2001)

In its founding definition, the Critical Zone was not theorized as being isolated from human influences. Yet, the central Critical Zone processes highlighted in the original NRC document focused on physical drivers and biology and did not explicitly address anthropogenic effects on Critical Zone processes or mechanisms. The original CZS framework, therefore, was primarily useful for earth scientists who engaged with focused interdisciplinary research drawing from closely related disciplines. As such, significant research into human impacts and disturbance effects on Earth systems did not receive sustained attention from Critical Zone scientists, especially early in CZS. The focus of research published since the development of the National Science Foundation (NSF) program on Critical Zone Observatory (CZO) sites underscores that many Critical Zone scientists are improving our understandings *of* the Critical Zone (Brooks et al., 2015; Broxton et al., 2015; Docherty et al., 2015; Lohse et al., 2009; Zapata-Rios et al., 2016), but few studies have focused on the impacts of humans and disturbance agents *on* the Critical Zone (Allen et al., 2015; Orem and Pelletier, 2015; Reale et al., 2015). Similarly, few early CZS studies addressed the spatial connectedness of processes across the geographic template *within* the context of the Critical Zone (Goddéris and Brantley, 2013; Pelletier et al., 2013; Pelletier and Orem, 2014). Building on this early work in CZS, in 2012 the NSF revised its guidelines for the CZO program with the directive that funded research should predict Critical Zone response to anthropogenic processes, in addition to focusing on resilience of the Critical Zone "in the face of land use change and climate change…to inform strategies for sustaining a wide range of human activities" (National Science Foundation, Critical Zone Observatory National Office). As a result of the NSF's updated programmatic directive to the CZO, recent funding has been awarded to a series of "2nd generation CZ observatories" (https://criticalzone.org/calhoun/about/) that deliberately incorporate human influences into their research programs (Richter et al., 2018). CZOs with research agendas specifically addressing anthropogenic impacts include Calhoun in South Carolina, which studies recovery of agriculturally degraded and eroded lands; Reynolds Creek in Idaho, which includes prescribed fire in its research; and the Intensively Managed Landscapes CZO in Illinois, Iowa, and Minnesota, which addresses human activities such as agriculture and land use (http://criticalzone.org/national/). The renewed focus of CZS on physical rates, fluxes, and processes, coupled with human impacts to intercoupled biotic and abiotic systems, provides CZS with powerful tools for explaining the rapid changes of the Anthropocene.

2.2 A Multidisciplinary, Cross-Scale Science

In his seminal paper "The Use and Abuse of Vegetational Concepts and Terms," Sir Arthur Tansley (Tansley, 1935) coined the term 'ecosystem' as "the whole complex of physical factors forming what we call the environment of the biome—the habitat factors in the widest sense.” Tansley intended the term to be inclusive of both physical and biological features as ‘one physical system’ (Richter and Billings, 2015), but Tansley’s early conceptualization was frequently overlooked by ecologists who delved into niche studies focused predominantly on the biological component of ecosystems. Earlier studies by (Merriam, 1898) and (Shreve, 1915), which led to the ‘gradient ecology’ theory of Whittaker and Niering, further established the close and co-constructive relationship between biotic components of ecosystems and their physical environment (Whittaker, 1967; Whittaker and Niering, 1975). Ecosystem ecology, which developed out of terrestrial ecology, began quantifying flows of energy and matter at ecosystem scales and frequently invoked anthropogenic effects on ecosystems as a driver of change (Odum, 1971). In ecosystem ecology, the spatial and temporal limits of ecosystems are not always addressed or as tightly defined as in CZS (Richter and Billings, 2015). Similarly, Earth and environmental scientists, sometimes in partnership with CZS, have a strong tradition of research that investigates processes of anthropogenic change in biotic and abiotic systems (*e.g.*, Ellis and Ramankutty, 2008; Williams et al., 2015). This approach acknowledges that anthropogenic effects on biophysical processes creates hybrid associations that cannot be ascribed to wholly “natural” or “human” causes (Dearing et al., 2015; Moreno-Mateos et al., 2017; Richter et al., 2018).

Despite strong similarities to biogeography and ecosystem ecology, CZS focuses more on the underlying processes and mechanisms crucial to supporting life on Earth (Chorover et al., 2007; Giardino and Houser, 2015; Richter and Billings, 2015). This mechanistic and quantitative approach to Earth Science research was borne out of a need to connect closely aligned subfields in a coherent multidisciplinary framework. CZS was defined and has developed to approach fundamental scientific questions about the Earth from the perspective of understanding and modelling Earth processes and mechanisms (Banwart et al., 2011; Giardino and Houser, 2015). The rapid expansion of interest in CZS and CZOs is a testament to the growing need to provide empirical evidence of changes in environmental processes and mechanisms to policy-, law-, and other decision-makers (Banwart et al., 2013; Field et al., 2015). CZS is not a departure from existing interdisciplinary sciences, such as ecosystem ecology, which have a long history of research into interconnections of hydrology, soils, and living systems. The novelty of the Critical Zone is in its vertical boundedness and in its expansion of historically “superficial” investigation of belowground terrestrial ecology (Richter and Billings, 2015). This novel framing does not radically transform the types of questions and the research methods that are employed in Critical Zone studies, compared to prior work on the connections between biological, geological, hydrological, and chemical components of ecosystems, but it does define a new unit of analysis that suggests a common focus on which interdisciplinary teams can centre their research.

Recently, researchers have begun to frame Critical Zone processes and fluxes in the context of ecosystem services—a clear recognition of the importance of coupled human-natural systems and ecological thinking in the operating in the Critical Zone. Ecosystem services are frequently understood to include the provisioning of material and energy, regulating the rates and amplitude of ecosystem processes, creating essential habitat and structure for biota, and providing culturally important functions (de Groot et al., 2010; Field et al., 2015, 2016; Watanabe and Ortega, 2011). As such, ecosystem services represent one strategy for incorporating the needs, desires, and impacts of humans on processes and fluxes occurring within the Critical Zone, but this incorporation tends to regard human societies as a beneficiary of ecosystem services rather than centring humans as agents capable of altering the rates, fluxes, and processes that occur within the Critical Zone. While examining Critical

Zone processes within the framework of ecosystem services improves the multidisciplinarity of CZS by extending Critical Zone research into the social sciences, it does not address the critical role of humans as a potentially dominant source of change in the Critical Zone. Critical Zone processes are understood to influence people, even as anthropogenic effects on Critical Zone processes have gone largely uninvestigated (but see Richter and Mobley, 2009; Moraetis et al., 2015; Guo and Lin 2016; Coughlan et al., 2017; Kumar et al., 2018). At sites where anthropogenic landscape changes are explicitly studied, such as the Intensively Managed Landscapes CZO in Illinois, Iowa, and Minnesota, most of the publications from these sites focus on biophysical process rather than on human effects – leaving an opportunity for researchers who implicitly link their work within a human-natural system. This is perhaps best illustrated by the research team at the Calhoun CZO in South Carolina, which since 2013 has investigated human-forced alterations to rooting depth, soil fertility, hydrology, and vegetation recovery in a landscape of reforested and heavily gullied abandoned agricultural fields.

2.3 Physical Processes in the Critical Zone – a Potential Unifying Theory

Rasmussen et al. (2011, 2015) provide a useful modelling framework—Effective Energy and Mass Transfer (EEMT)—for conceptualizing and studying Critical Zone processes. EEMT is based upon thermodynamic theory in that fluxes of mass and energy into and through the system drive internal cycling processes. EEMT integrates the structures and functions of interacting components of the Critical Zone and defines several terms that can be used to articulate the influences of anthropogenic and ecological disturbance (*e.g.*, changes in land use, hydrologic alterations, and wildfire) on Critical Zone processes. This model provides an opportunity for biogeographers to integrate their observations of pattern through use of a unifying model:

$$E_{TOTAL} = E_{ET} + E_{PPT} + E_{BIO} + E_{ELEV} + E_{GEO} + \sum E_i \qquad (1)$$

where E_{ET} is latent heat flux from terrestrial evapotranspiration, E_{PPT} is energy flux from effective precipitation, E_{BIO} is energy flux from net primary production, E_{ELEV} is energy flux from uplift and/or physical denudation, E_{GEO} is energy flux from chemical denudation, and ΣE_i represents any other energy and mass transfer (Rasmussen et al., 2015). We use this model to examine the ways in which anthropogenic and ecological disturbance can have divergent effects on Critical Zone rates and processes in our discussion of praxis that follows.

3. Contributions from Biogeography and Spatial Ecology Theory and Praxis for Study of the Critical Zone

Biogeography and global ecology do not inherently address questions of human impacts on the Critical Zone, although both disciplines often conduct research relevant to anthropogenic effects on Critical Zone processes and can be uniquely equipped to deal with questions of human influence at a variety of scales. Expanding emerging efforts to include anthropogenic influences into Critical Zone research (see Brecheisen, 2018; Coughlan et al., 2017; Kumar et al., 2018; Moraetis et al., 2015) would help shift CZS from a *multidisciplinary* collection of epistemologically similar physical and biological sciences to a holistically *interdisciplinary* enterprise that includes biogeographical methodologies and is prepared to address the questions of human influence and ecological disturbance operating at variable scales on the Critical Zone in the Anthropocene.

3.1 Theory ~ Biogeography and Spatial Ecology Approaches to Community Organization and Disturbance; NeoClementsian Implications in the Anthropocene

Ecology and biogeography have had a long theoretical and framing debate about the nature of ecological systems and their components, particularly the stability and predictability of the relationships between community constituents and the relationships among communities and community members (organisms) across spatial gradients. The composition, constituency, and behaviour of ecological communities can have implications for how communities respond to ecological and anthropogenic disturbance, which can be linked to Critical Zone processes. As anthropogenic and ecological disturbances radically reshape ecological communities, the ways in which Critical Zone scientists and biogeographers view ecological relationships in space and time has profound implications for how we understand the Anthropocene.

Frederic Clements (Clements, 1916) argued that ecological communities function as superorganisms, with predictable, deterministic, and characteristic formation, stages of development, and response to disturbance. In contrast, Henry Gleason (Gleason, 1917) suggested that initial conditions and the various exigencies of community formation create assemblages, and that those assemblages are not stable or predictable over time and space. Contemporary biogeographical research contains residues of the tension between theorizing ecological associations as stable and predictable, and understanding that the patterns of species distributions are a result of historical accident as well as the capacity of organism to adapt to changing conditions (Christensen Jr, 2014). Biogeographers and ecologists routinely refer to concepts such as biomes and life zones, which represent broad-scale assemblages of plants and animals that are principally influenced by climatic factors, most importantly temperature and precipitation regimes. At the same time, both disciplines recognize that colonization events, disturbance, and vicariant episodes have a profound influence on species ranges and geographic distributions of a broad suite of taxa.

Critical Zone Science unites diverse scientific research questions into a unified disciplinary framework and attempts to tease out the dynamism at and near the Earth's surface (Rasmussen et al., 2011). CZS tends to capture community-level response to environmental conditions, and unless approached from a position of careful articulation of community development and contingent response to disturbance, risks reiterating long-abandoned Clementsian understandings of ecological trajectories. The potentially Clementsian outlook of CZS is revealed through measurements using ecosystem flux towers, which estimate net primary production and total community photosynthesis and respiration regardless of community constituents. Ecosystem flux measurements often include soil respiration, which is often conducted without comprehensive understanding of the microbial and belowground community being measured. Approaches and targeted measurements that help disentangle complex interactions are critical to the attribution of ecosystem-level patterns to specific ecosystem constituents.

By structuring a research agenda that conceptualizes the environment extending from the top of the vegetation canopy down to the deepest circulating groundwater/rock interface (Banwart et al., 2011) as a singular entity that can be studied, measured and modelled across time and space, CZS risks reviving Clementsian ideas about ecology and community organization. CZS is best positioned to consider the amplified disturbances that characterize the Anthropocene when factors such as land use, prior disturbance, and contemporary and historical biotic communities are taken into consideration. Intentional or not, the potential return to Clementsian views of nature has implications for the types of insights of which CZS is capable and intended. For example, as scientists gain a deeper understanding of the differential physiological limitations imposed by mixed species and even individuals of varying ages (McDowell et al., 2005), the importance of the precise constituency and structure of community assemblages becomes more apparent. Modifying the apparent superorganismal approach of CZS to account for more refined understandings of community organization and formation allows more subtle insights into Critical Zone processes, and this represents an important opportunity for biogeographers and ecologists. Such a shift in theoretical focus will also assist biogeographers and spatial ecologists in applying CZS insights to explain ecological pattern and process at scales ranging from sites to landscapes, regions, and the globe.

Some abiotic aspects of Critical Zone processes do not align perfectly with Gleasonian-Clementsian conceptions of the nature of ecological communities and their responses to disturbance. Groundwater circulation and deep mineral weathering, for example, are likely not affected by the precise constituency of aboveground and belowground vegetation and microbial communities. Other abiotic Critical Zone processes, such as erosion rates, are strongly affected by vegetation-mediated processes that can be dramatically altered by aboveground disturbance, but likewise depend in part on the composition of the vegetation communities. In this way, the connections between individuals and how they scale spatially (*sensu* foundational work: Arrhenius, 1921; Harte and Kinzig, 1997; Preston, 1960) are important as we think about upscaling physical processes and fluxes. Scaling of ecological communities and associated biophysical processes in space and time must incorporate responses to disturbances.

Similar to concerns about the importance of community assemblages, CZS can be approached either by theoretical reliance on general principles as explanatory agents, or on system-specific elements that are used to characterize the syncretic enterprise of Critical Zone studies. In this sense, orientation towards research can modulate between general principles with a deductive approach (Newtonian) and specific cases with an inductive approach (Darwinian) conceptualizations of the Critical Zone and its role in associated systems (Jenerette et al., 2012). Newtonian approaches to Critical Zone studies include reductive modelling, such as the EEMT model (Rasmussen et al., 2015), which allows for broad characterization of thermodynamic influences across the Critical Zone by focusing on several strongly predictive variables. Newtonian approaches favour explication of mechanism and process through general overarching rules and carry considerable explanatory power. Darwinian methodological approaches rely on a deep understanding of interlocking elements of the systems under study, from which general rules can be developed, similar to an inductive strategy of research. Darwinian-Newtonian theorizations of complex systems can aid Critical Zone scientists in conceptualizing abiotic interactions that are poorly captured by Gleasonian-Clementsian understandings of aboveground ecological communities. We argue that a research agenda that animates ecological theory via an inductive approach towards community composition and behaviour can provide powerful insight into anthropogenic effects on Critical Zone processes. This approach provides the best opportunity for synergy between biogeography and CZS (Figure 1), although deductive and superorganismal theoretical approaches to the Critical Zone can and will continue to yield important results. Via this theoretical framework, Critical Zone scientists can arrive at a foundation that supports robust study into the interactions between Critical Zone rates and processes with changes to ecological communities and the confounding effects of natural and anthropogenic disturbance. This process respects Tansley's concept of an integrated ecosystem and draws upon the theoretical heft of modern biogeography to produce a comprehensive approach to view mechanisms and processes at variable spatial and temporal scales in the Critical Zone (Tansley, 1935).

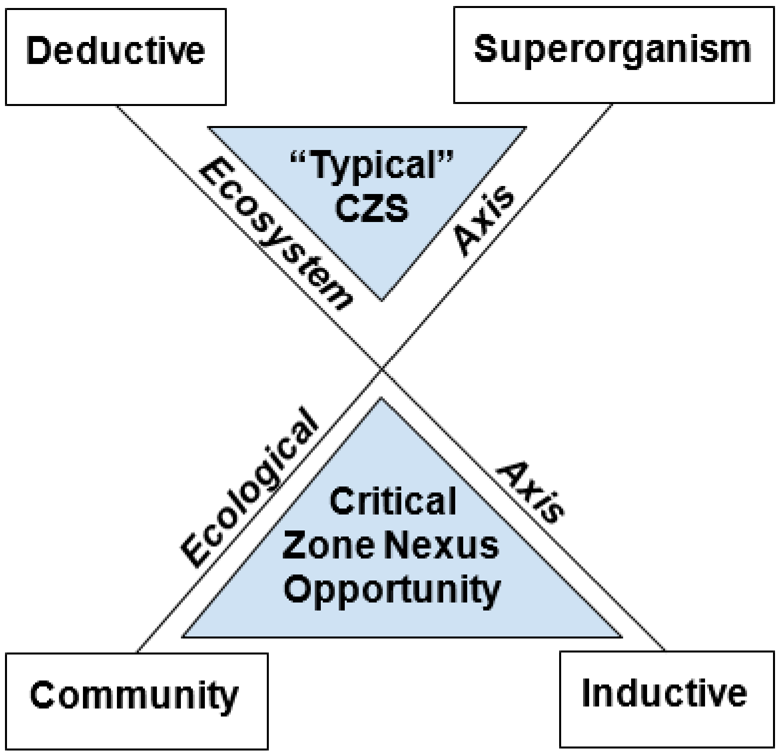

Figure 1: Critical Zone Science can be approached from multiple theoretical starting positions: conceptions of ecological communities and post-disturbance trajectories that favour recognising community makeup versus viewing communities as predictable "superorganisms"; and an orientation towards research that prefers general principles (deductive approach) versus system-specifics (inductive approach). We argue that CZS has the greatest capacity to incorporate the effects of disturbance, and best characterize human effects on Critical Zone processes, when oriented towards the Community and Inductive poles - a "Critical Zone Nexus Opportunity," sensu Tansley (1935).

The specific and particular components of ecological communities have important and as-yet poorly characterized impacts on Critical Zone processes (Community pole, Figure 1). The precise effects of human influences on various components of Critical Zone processes and rates, as theorized by the EEMT methods, is best approached through a deep understanding of system specifics (Inductive pole, Figure 1). By situating their research agendas and their conceptualizations of integrated ecosystems (*sensu* Tansley, 1935) in the space between the Community and Inductive poles, Critical Zone scientists can successfully integrate 'hot moments' (punctuated ecological disturbance and accelerating anthropogenic changes) with 'hot spots' (geographically-bounded alterations to the Critical Zone) through studies into the mechanisms and processes of the Critical Zone across spatial and temporal scales.

3.2 Praxis ~ Biogeography as Spatial Ecology, with Disturbance Defined as 'Hot Spots' & 'Hot Moments'

Critical Zone Science is centred on a sophisticated understanding of time-sensitive rates and processes that vary widely along temporal scales. Despite the capacity of disturbance to affect Critical Zone processes, CZS has not historically investigated disturbance across spatial or temporal scales. Punctuated disturbance events have the capacity to dramatically alter rates at which Critical Zone processes occur, with profound effects for the fluxes of materials and energy across Critical Zone boundaries. Accelerations in rate processes in the Critical Zone can occur either spatially ('hot spots') or temporally ('hot moments'), or both spatially and temporally simultaneously (McClain et al., 2003). 'Hot spots' can be highly variable across spatial scales and gradients, and can range from geographically constrained to spatially amorphous, with correspondingly variable effects on subsystems of the Critical Zone. 'Hot moments,' similarly, represent punctuated events or short periods of time during which Critical Zone rates accelerate or slow. Examples include decomposition rates that are dramatically accelerated by combustion (Kurz and Apps, 1994; Neary et al., 1999), soil transport speeded up by overland flow (DeBano, 2000; Swanson and Dyrness, 1975), and soil carbon loss following anthropogenic vegetation clearing (Guo and Gifford, 2002; Murty et al., 2002). Consideration of spatial and temporal variabilities in material and energy fluxes occurring in distinct portions of the Critical Zone initiated by ‘hot spots’ and ‘hot moments’ can improve our understanding of rate-dependent fluxes in the Critical Zone and their impacts on biotic patterns and function. Further, this refinement allows for closer alignment of CZS with biogeography’s study of disturbance across spatial and temporal scales.

As an exercise in illustrating the potential effects of disturbance on Critical Zone processes and fluxes, we examine the implications of five types of disturbances (themselves representative of a hybrid of anthropogenic and ecological sources) on the central inputs and outputs of Critical Zone function through the lens of the integrating EEMT model in Equation 1 (Rasmussen et al., 2015; Figure 2). Again, this is a means by which biogeographers and ecologists can extend research effort into a broader context and also a process that can potentially explain variation found across global spatial scales by integrating a better understanding of the temporally and vertically complex physical environments of the Critical Zone. Specifically, we investigate the effects of disturbances (‘hot moments’) in the form of wildfire and drought, as well as longer-term processes such as land cover change in the form of urbanization, afforestation and reforestation, and the effects of the enhanced greenhouse effect (Table 1). These disturbance types are not wholly “natural” or anthropogenic, but arise from combinations of ecological and human influence and as such should be viewed as hybrid socio-natural events, particularly as we move farther into the Anthropocene. Published scientific literature does not always identify a single directional change in flux due to a disturbance effect in isolation from correlated factors, so we present multiple lines of evidence wherever possible. In fact, the multiple directionalities associated with these input and output parameters underscore the utility of a multi-disciplinary observatory network where seemingly disparate processes can be co-monitored and measured through time.

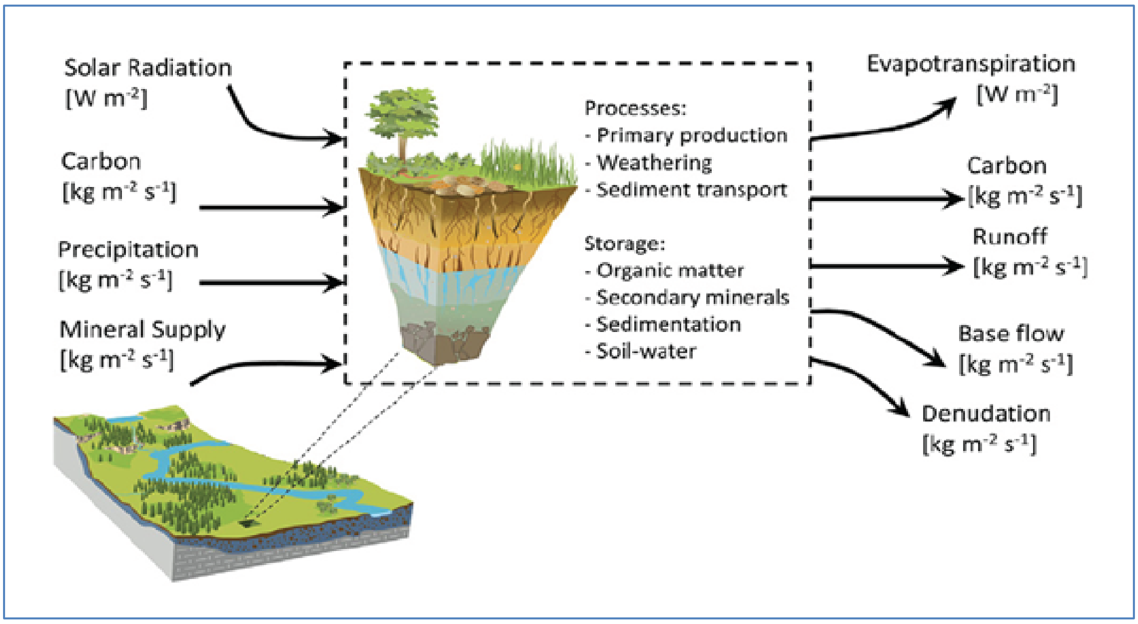

Figure 2: Critical Zone rates and fluxes corresponding to the constituents of the Effective Energy and Mass Transfer (EEMT) model. Each flux into and out of the Critical Zone can be significantly influenced by disturbance, but remain understudied in the integrated nature now characteristic of Critical Zone science. Figure used with permission from Rasmussen et al., 2015.

	Major Fluxes	Fire	Reforestation	Temperature	Drought	Urbanization
Inputs	Solar Radiation	↑	↑	↑	↑ (↓)	↓
	Carbon	↓ (↑)	↑	↑	↓	↓
	Mineral Supply	↑	↑	↓	↓	↑
	Precipitation	↑	Locally ↑/↓	Locally ↑/↓	↓	↓
Outputs	Evapotranspiration	↓	↑/↓	↑	↑/↓	↓
	Carbon	↑ (↓)	↓	↑/↓	↑ (↓)	↑
	Runoff	↑	↓	↓	↓	↑
	Base Flow	↑	↓	↓	↓	↓
	Denudation	↑	↓	↑	↑	↑

Table 1: Major flux changes resulting from anthropogenic and ecological disturbance, as expressed through altered inputs and outputs contained in the expanded Effective Energy and Mass Transfer (EEMT) model (Figure 2; Equation 1; Rasmussen et al., 2011, 2015). Parentheses around arrows indicate that under some conditions or according to some authors, the vector of change can be in that direction.

Wildfire

Disturbance from wildfire generally results in increases in EEMT outputs (Figure 2), but inputs tend to be more variable. Burned areas experienced increased insolation and precipitation, both due in part to reduced canopy cover (Hart et al., 2005). Fire effects on mineral supply is more difficult to characterize, as many minerals are lost through erosion, combustion, and volatilization after areas are burned (Schindler et al., 1980). However, availability of certain crucial minerals, principally nitrogen, may increase (Hart et al., 2005; Neary et al., 1999). Net carbon inputs are generally reduced in burned areas, even as inert soil charcoal may increase (Hart et al., 2005; Neary et al., 1999). On the other hand, increases in some EEMT outputs, including runoff, streamflow, baseflow, and denudation, are intuitive and are borne out by evidence (DeBano, 2000; Dunham et al., 2007; Hart et al., 2005; Jones and Post, 2004; Kinoshita and Hogue, 2011; Price, 2011; Schindler et al., 1980). While there is limited research on the impact of wildfire on evapotranspiration, remote sensing-based studies show reduced evapotranspiration following wildfire (Poon and Kinoshita, 2018; Sánchez et al., 2015), likely due to changes in vegetation structure land surface temperature, and albedo (Sánchez et al., 2015) (Table 1).

Afforestation and reforestation

While processes of afforestation and reforestation might be expected to yield EEMT flux changes inverse to wildfire-induced fluxes (Figure 2; Table 1), evidence shows that this is not always the case. For example, solar radiation input increases with afforestation and reforestation, but only if that input is defined as absorption of incoming radiation by vegetation canopy (Arora and Montenegro, 2011; Matthews et al., 2007). Mineral supply and precipitation inputs are more difficult to determine, as both vary based in part upon scale and considered processes. Afforestation effects on global precipitation patterns are complex (Stark et al., 2016; van Dijk and Keenan, 2007), but local afforestation might produce local increases in precipitation (Swann *et al*., 2012). Afforestation may increase mineral soil nitrogen concentrations (Liu et al., 2018). Carbon, most simply accounted for by sequestration in vegetation, increases as an EEMT input and decreases as an EEMT output (Figure 2; Bonan, 2008; Kolbe et al., 2016; Liu et al., 2018, 2018; Paul et al., 2002; Post and Kwon, 2000). Denudation decreases, as a greater percentage of land is covered following afforestation and reforestation (Schaller et al., 2018). Runoff and base flow also appears to decrease (Bassiouni and Oki, 2013; Farley et al., 2005; Price, 2011; Zhang et al., 2004), while, similar to post-fire fluxes, evapotranspiration is more difficult to categorize as positive or negative. In some systems, evapotranspiration likely decreases following afforestation efforts (Liu et al., 2008) while in others, evapotranspiration likely increases (Price, 2011; Trabucco et al., 2008) (Figure 2; Table 1).

Increasing temperature

Increasing global temperatures will cause variable responses for Critical Zone fluxes (Figure 2) across spatial and temporal scales (Bonan, 2015). Surface temperature gradients across the earth are most basically dictated by amount and duration of incoming solar radiation. Although a warmer world via increasing radiative forcing will not change the amount of solar radiation received at the top of the atmosphere, corresponding variations in cloud cover and cryosphere will alter both planetary and local albedo, and thereby the amount of insolation received at the surface. Insolation will likely decrease in some locations from indirect causes such as solar dimming and increased concentrations of atmospheric water vapor and dust (Alpert et al., 2005; Held and Soden, 2006), while other locations will see increased insolation from expansion of Hadley Cell doldrums, loss of cloud cover, and decreased reflectivity (Byrne and O'Gorman, 2015; Hall and Qu, 2006; Held and Soden, 2006).

As with afforestation and reforestation, increased variability of precipitation at local scales will likely result from global temperature increases (Byrne and O'Gorman, 2015; Held and Soden, 2006; Pascale et al., 2017). Globally, the water cycle is expected to intensify: global mean runoff will decrease, latitudes greater than 40° N/S will see increases in total precipitation due to the warming atmosphere, and mid-latitudes will experience more variable precipitation (Byrne and O'Gorman, 2015; He and Soden, 2017; Held and Soden, 2006; Huntington, 2006; Pascale et al., 2017; Zhang et al., 2014). Mineral supply is dependent upon bedrock source, the mineral and ecosystem in question, and a host of other factors (Addiscott and Whitmore, 1987; Torn et al., 1997), and cannot be reduced to a single directional change. Warmer temperatures and increased precipitation typically imply increased chemical weathering of rocks, which in turn strengthens the fluxes of silicates and carbonates (Brady, 1991). Carbon inputs from the atmosphere and biosphere are projected to increase, and temperatures will also enhance carbon inputs by releasing carbon from temperature sensitive storage sources such as permafrost (Kolbe et al., 2016; Natali et al., 2015; Trumbore et al., 1996) (Figure 2; Table 1).

Carbon outputs in non-permafrost regions, especially from soil carbon, may be more variable, especially as ecosystem sensitivity changes with increasing atmospheric carbon and temperatures (Davidson and Janssens, 2006; X Wang et al., 2014). Permafrost regions, however, will see dramatic releases of carbon (Schuur et al., 2015; Schädel et al., 2016; Winterfeld et al., 2018). Generally, evapotranspiration is likely to decrease as water use efficiency increases with increased atmospheric CO_2, thereby allowing for conservative stomatal openings in plants (Bonfils et al., 2017; Milly and Dunne, 2016). This, however, is not consistent across ecosystems where other factors are limiting growth. The direct effect of warming temperatures will theoretically increase evapotranspiration only if there is adequate water availability, or potential evapotranspiration is equal or greater than actual evapotranspiration (Huntington, 2006; Mankin et al., 2017; Milly and Dunne, 2016; Price, 2011). The coupled relationships between temperature and runoff can have variable impacts on chemical and nutrient availability that are likely to fluctuate over space and time (Brown et al., 2017; Eiriksdottir et al., 2013; Kirstein et al., 2016) (Table 1).

Drought

Drought, which leads to a series of changes in Critical Zone fluxes (Figure 2), is projected to increase globally in frequency and severity with future climate change (Dai, 2013). Drought can result in increased solar radiation input because of reductions in cloud cover (Charney, 1975), foliage loss (Bréda et al., 2006), and vegetation die-off (Breshears et al., 2005).

Drought may result in decreased solar radiation input, in part via increases in albedo based on foliage loss, evaporation of bodies of water, and other processes that affect surface reflectivity (Charney et al., 1977; Courel et al., 1984). Inputs of carbon and mineral supply are expected to decrease because of a reduction in Critical Zone rates, and precipitation decrease is a definitional component of drought. Mineral supply is indirectly affected in several ways, including by reduced nutrient uptake, reduced microbial activity (Sardans and Peñuelas, 2005), reduced mineral transport to the canopy with lowered transpiration rates (Hu and Schmidhalter, 2005), and an increase in energetic cost for nitrogen conversion (Farooq et al., 2009; Pinheiro and Chaves, 2011). Wallin et al. (2002) find that drought is the cause of reduced mineral nutrient concentrations in Norway spruce needles. Carbon input may decrease, including as gross ecosystem uptake (Reichstein et al., 2002), ongoing storage and stocks (Brando et al., 2008), and assimilation (Dreyer, 1997; Schulze, 1986). Carbon output may increase, in part due to soil respiration (affected by ecosystem type and seasonality; (B Wang et al., 2014). For example, high carbon emissions from moist tropical forests during droughts have been observed (Houghton et al., 2000). Baseflow is expected to decrease, as is runoff (Dahm et al., 2003; Dai et al., 2008), due to decreased water availability. Drought impacts on evapotranspiration depend on the duration and severity of drought and the antecedent moisture conditions. Evaporation generally increases due to increased wind speed and reduced cloud cover (Dai, 2011), and transpiration decreases as plants close their stomata to conserve water (Cinnirella et al., 2002; Irvine et al., 1998; Limousin et al., 2009; MacKay et al., 2012). Finally, drought generally increases erosion (Allen and Breshears, 1998; Davenport et al., 1998) and therefore denudation may be expected to increase (Schaller et al., 2018) (Table 1).

Urbanization and Development of Human-Dominated Landscapes

Of the anthropogenic disturbances discussed here, urbanization is perhaps most likely to result in altered Critical Zone fluxes (Figure 2; Table 1). The most striking effects relate to land cover change and loss of vegetation canopy, in concert with hardening of surfaces and changes to radiative budgets. Decreases have been observed for surface solar radiation (Alpert et al., 2005) and carbon inputs, the latter with straightforward negative impacts on net primary productivity (Imhoff et al., 2004). Studies suggest that mineral supply input into watersheds increases with urbanization (Kaushal et al., 2011; Taka et al., 2017). Urbanization can result in accelerated chemical denudation, probably because of increased atmospheric acidity and enhanced runoff within the urban system (Prowse, 1987). The impacts of urbanization on precipitation are likewise difficult to determine, though there is much literature regarding changes in large- and small-scale hydrological scales as a result of urbanization, and in particular urban heat islanding has been shown to decrease precipitation (Diem and Brown, 2003; Milly *et al.*, 2008). Further, precipitation that enters the groundwater pool is also likely to decrease (Arnold Jr and Gibbons, 1996). Evapotranspiration may decrease overall (Carlson and Arthur, 2000). Perhaps most surprisingly, Kaye et al., (2005) finds that carbon outputs, via soil respiration and belowground carbon allocation, are greater in urban ecosystems than in any other land-use type. Finally, while runoff may increase (Leopold, 1968; Dow, 1997; Carlson and Arthur, 2000), base flow to streams may be significantly reduced (Simmons and Reynolds, 1982).

FINAL REMARKS - Opportunities for Biogeographic and Ecological Theory and Praxis to Drive Earth Science Integration

Disturbances produce measurable perturbations that are significant at temporal (‘hot moment’) or spatial (‘hot spot’) scales. Anthropogenic disturbances have the potential to amplify ecological disturbance, and to push systems out of stationarity and to produce non-analogue ecosystems, all of which will be reflected in altered fluxes in and through the Critical Zone. Here we have shown how a Critical Zone approach both integrates the physical science disciplines (a Newtonian approach) and relies on the specifics of the interacting abiotic-biotic connections (a Darwinian approach). The temporal and spatially variable terms included in EEMT calculations provide an ideal lens and an integrating model through which biogeographers, ecologists, and Critical Zone scientists can apply deliberate study of disturbance into Critical Zone processes and to characterize accelerating changes in the Anthropocene. The role of individual organisms and species, spatio-temporal variations in species responses, and the potential for plasticity in organismal response in space and time are clearly under-represented in current Critical Zone Science (CZS) approaches and the unifying EEMT model. Better integration of biogeography and CZS represents a rich opportunity for insights from a deeper understanding of biogeographical and ecological processes, both temporally (ranging from the generation scale of particular organisms through to geologic timescales) and spatially (*i.e.*, the deep Critical Zone (Buss et al., 2013; Chorover et al., 2011) to drive Earth Science forward. Now that many of the original CZ Observatories have over a decade of data and the US National Science Foundation is moving from a more "Observatory" to "Network" model, the opportunities for geographers to integrate into this effort are even greater.

Experimental designs based on ecological theory and practice, adaptation of metrics (*e.g.*, with insights from the EEMT or other CZS models), and consideration of the spatial implications of Critical Zone fluxes can all help productively couple the disciplines of biogeography and CZS even further. Biogeography has deep roots in integrating these disciplines, having been built by pioneers of atmosphere, hydrosphere, and lithosphere research. By continuing to incorporate the effects of disturbance and anthropogenic influences on Critical Zone processes, rates, structures, and sites, the multidisciplinary and multiscalar enterprise of CZS and the established field of biogeography can more fully characterize the dynamism and rapid changes that define the Anthropocene.

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