Critical Zone Services: Expanding Context, Constraints, and Currency beyond Ecosystem Services

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Processes within the critical zone—spanning groundwater to the top of the vegetation canopy—have important societal relevance and operate over broad spatial and temporal scales that often are not included in existing frameworks for ecosystem services evaluation. Here we expand the scope of ecosystem services by specifying how critical zone processes extend context both spatially and temporally, determine constraints that limit provision of services, and offer a potentially powerful currency for evaluation. Context: A critical zone perspective extends the context of ecosystem services by expressly addressing how the physical structure of the terrestrial Earth surface (e.g., parent material, topography, and orography) provides a broader spatial and temporal template determining the coevolution of physical and biological systems that result in societal benefits. Constraints: The rates at which many ecosystem services are provided are fundamentally constrained by rate-limited critical zone processes, a phenomenon that we describe as a conceptual “supply chain” that accounts for rate-limiting soil formation, hydrologic partitioning, and streamflow generation. Currency: One of the major challenges in assessing ecosystem services is the evaluation of their importance by linking ecological processes to societal benefits through market and nonmarket valuation. We propose that critical zone processes be integrated into an evaluation currency, useful for valuation, by quantifying the energy flux available to do thermodynamic work on the critical zone. In short, characterization of critical zone processes expands the scope of ecosystem services by providing context, constraints, and currency that enable more effective management needed to respond to impacts of changing climate and disturbances.

Abbreviations: EEMT, Effective Energy and Mass Transfer.

The critical zone is defined as the portion of the Earth’s land surface that extends from the lower limit of freely circulating groundwater to the top of the vegetation canopy (NRC, 2001). Functioning of the critical zone determines the rates at which many ecosystem services (e.g., Costanza et al., 1997; MEA, 2005; TEEB, 2010), emphasizing how biodiversity, ecological processes, and spatial patterns in the near-surface environment provide services to society. Environmental scientists and economists have addressed the need to link biophysical processes to human well-being through the developing concept of ecosystem services (e.g., Costanza et al., 1997; MEA, 2005; TEEB, 2010), emphasizing how biodiversity, ecological processes, and spatial patterns in the near-surface environment provide services to society. Four categories of ecosystem services were initially identified: (i) provisioning services describe the material or energy outputs from ecosystems and include food, water, and other resources; (ii) regulating services influence processes such as water quality, flood regulation, and disease regulation; (iii) habitat or supporting services consider...
A critical zone perspective places different emphasis on services that lead to services, and (iii) offer a potentially relevant unified currency for the evaluation needed before valuing ecosystem services. We briefly discuss each of these three points—context, constraints, and currency—and then explore them more thoroughly in the sections below.

A critical zone perspective extends the context of ecosystem services by expressly addressing how the physical structure of the terrestrial Earth surface (e.g., parent material, topography, and orography) provides a broader spatial and temporal template determining the coevolution of physical and biological systems that result in societal benefits. More specifically, a critical zone perspective expands the traditional focus on ecological processes and spatial patterns in the near-surface environment by considering the full extent of the vertical weathering profile (a geomorphic template wherein bedrock production of saprolite and soil supports the establishment of the vegetation canopy), allowing improved integration of processes that determine constraints that limit provision of ecosystem services. Rates at which many ecosystem services are provided are fundamentally constrained by critical zone processes (Chadwick et al., 1999; Rockström et al., 2009; Dominati et al., 2010). We describe this as a conceptual “supply chain” that accounts for rate-limiting processes, such as soil formation, hydrologic partitioning, and streamflow generation. One of the major challenges in assessing ecosystem services is linking ecological processes to societal benefits through market and nonmarket valuation; we propose that critical zone processes can be integrated into a currency that can be used for more effective management and evaluation of ecosystem services. We propose that an energy-related metric can aid in the evaluation and valuation of ecosystem processes and services occurring in the critical zone, similar to those proposed in the ecological economics literature (e.g., Patterson, 1998). One such energy-related currency is the capacity to perform physical and chemical work on the subsurface (Rasmussen et al., 2011; Kleidon et al., 2012), which permeates multiple spatial and temporal scales relevant to the critical zone.

Context

The context of an environmental system identifies key components of a system of interest and how these components relate to each other and to fundamental processes within the system. Ecosystems are climate-sensitive drivers of long-term critical zone evolution (Chadwick et al., 1999; Rasmussen et al., 2011), and the evolved structure of porous soil and bedrock affects how an ecosystem responds to perturbation (Lin, 2010). Services are the ways in which physical and biogeochemical processes (e.g., soil formation) provide benefits to society. Services deriving from critical zone processes provide expanded context in that they are sensitive to how climatic and lithologic variations affect the long-term evolution of soil and regolith (Fig. 1). Services include conversion of minerals and nutrients from unavailable lithic forms to biologically available forms, weathering-induced carbon sequestration,
“supply chain” that accounts for rate-limiting processes such as soil processes within the critical zone relative to societal demands (Fig. 1). A guiding framework for describing the functioning of the critical zone services provide context, constraints, and currency that enable more effective management and valuation of ecosystem services (adapted from MEA, 2005).

Fig. 1. Critical zone services provide context, constraints, and currency that enable more effective management and valuation of ecosystem services (adapted from MEA, 2005).

Constraints
Constraints provide location-specific limits for both goods and services. The amount and rates at which ecosystem services are provided are fundamentally constrained by the geologic and biologic processes within the critical zone relative to societal demands (Fig. 1). A guiding framework for describing the functioning of the critical zone (and consequently ecosystem functioning) is a conceptual “supply chain” that accounts for rate-limiting processes such as soil formation (Heimsath et al., 1997), carbon stabilization (Torn et al., 1997), groundwater recharge (De Vries and Simmers, 2002; Green et al., 2011), and hydrologic partitioning (McGuire and McDonnell, 2006). Processes and associated services are controlled by rate-limiting steps that constrain the ability of the system to supply societal benefits (e.g., López-Hoffman et al., 2013), providing an extended perspective of this analogous supply chain.

Hence, the rate at which society benefits from ecosystem services is ultimately dependent on rate-limiting critical zone processes. These processes operate over geologic time scales (thousands to millions of years) rather than those time scales traditionally associated with ecosystem succession (tens to hundreds of years) and may also extend into much greater depths (hundreds of meters) than is typically studied by terrestrial ecosystem scientists (Riebe et al., 2015). Therefore, a better bridge is needed to quantify the effects of those critical zone services, thus expanding the context and time scale of the supply chain. By explicitly considering larger spatial and temporal scales and associated critical zone processes, we can enable land managers to better predict anticipated deliveries of ecosystem services; that is, they would consider the supply chain more explicitly. Achieving this goal will require effective translation of critical zone research for land management clientele. A key factor affecting the supply chain of critical zone services is disturbance, such as wildfire, which alters a slow process, such as soil formation with a series of rapid processes, such as organic matter loss and erosion (González-Pérez et al., 2004; Mataix-Solera et al., 2011). By considering critical zone processes, one can better manage ecosystem services in the context of disturbances. This shift in thinking is important because disturbances are a key modulator, interrupting or catalyzing ecosystem services, or, in some cases driving “dis-services,” which have negative effects on society (e.g., post wildfire flooding destroying infrastructure, or negative hydrological and microclimate change following drought-triggered forest die-off) (Schröter et al., 2005; Lyytimäki et al., 2008; Lyytimäki and Sipilä, 2009; deGroot et al., 2010; Breshears et al., 2011; Boyd et al., 2013).

Currency
Currency is critical to the evaluation of societally relevant processes and services that often are quantified in diverse units (currencies). A key challenge in using the concept of ecosystem services to integrate consideration of ecological processes into societal decision-making is valuation of ecosystem services (e.g., Foley et al., 2005; Wunder, 2005; Havstad et al., 2007; Robinson et al., 2012; Graham et al., 2013). Thorough ecosystem service valuation requires understanding the multiple ecological inputs for a given ecosystem service output, often expressed in different currencies (DeFries et al., 2005; Barbier, 2012; Parks and Gowdy, 2013). Many ecosystem processes underlying ecosystem services are complex and difficult to simplify and as such may be poorly understood by managers and decision-makers. The use of energy as a valuation currency by managers and decision-makers has been shown to be fundamental to accounting in ecosystems (e.g., Odum, 1957), and the foundation of ecological economics is based largely on energy accounting (e.g., Hall, 2004). Energy that does work in developing...
the structure of the critical zone (as quantified, e.g., by Rasmussen et al., 2011; Kleidon et al., 2012) is effectively stabilizing services into the future as opposed to energy that flows through the system quickly, providing limited services. For example, carbon storage or water storage in the critical zone is a valued service, but carbon in the atmosphere provides limited services and is in most cases considered undesirable (Banwart et al., 2013). Recently, a method was developed for quantifying the energy and mass flowing into the critical zone from effective precipitation and primary production into a simple collapsed metric, enabling an expanded approach for valuing ecosystem services (Fig. 1). This approach can be further expanded to include other relevant energy and mass fluxes into the critical zone. More specifically, critical zone processes can be integrated into an evaluation currency by quantifying the amount of energy available to perform physical, chemical, and biological work on the subsurface, described as Effective Energy and Mass Transfer (EEMT, expressed in W m\(^{-2}\); Rasmussen et al., 2011). The EEMT is a strong predictor of key critical zone characteristics, including soil development and regolith depth, aspect controls on critical zone properties, and mean water transit times (Broxton et al., 2009; Chorover et al., 2011). In this sense, EEMT is a simple collapsed metric of the key energy and mass fluxes through the critical zone that are directly related to critical zone processes and therefore may result in societal benefits through ecosystem services. By incorporating a metric such as EEMT in critical zone services evaluations, land managers cannot only assess current provision of services (ecosystem service approach) but also, and perhaps more importantly, the potential provision of services based on the available energy to perform ecosystem work, ultimately resulting in societal benefits. Although it is beyond the scope of this paper to specifically apply EEMT quantitatively, its application elsewhere has allowed, for example, researchers to compare the potential services provided by different soil types by expressing the degree of soil development in energy units (Rasmussen et al., 2011).

Expanding Ecosystem Services

We suggest that a critical zone perspective expands the current perspectives on ecosystem services in terms of context, constraints, and currency. With a longer time scale, more geo-cognizant perspective of services could aid in improving natural resource management (Fig. 1). Current perspectives on ecosystem services can effectively be expanded to incorporate critical zone processes explicitly, focusing more strongly on soils, weathered bedrock, and the role that the vertical profile below the surface plays in regulating climate and carbon storage, nourishing ecosystems, and controlling water quality and quantity (USEPA, 2013). The current framework often does not explicitly account for the interconnected nature of critical zone systems and the importance of critical zone processes in establishing surface flow networks, landscape connectivity, and groundwater flow systems.

Although many ecosystem services overlap directly with human management time scales, such as water quality and flood regulation, critical zone services require consideration of both shorter and longer time scales relative to human management (e.g., Vitousek et al., 2004). Importantly, for some services, explicit consideration of longer time scales relative to management time scales can inform and improve management (e.g., Rockström et al., 2009). Disturbances are a driving and recurring force over millennial critical zone time scales (e.g., Orem and Pelletier, 2015), but they are inherently disruptive over annual to multi-decadal time scales that correspond to ecosystem processes and management (MEA, 2005; TEEB, 2010). On the basis of these fundamental differences, we highlight several examples of how explicit consideration of critical zone services with respect to context, constraints, and currency can potentially help to improve management and valuation of ecosystem services (Table 1, building on Costanza et al., 1997; Haygarth and Ritz, 2009).

We pose the following actions as a catalyst for further advancing understanding of critical zone services within and beyond the relevant interdisciplinary research communities: (i) partnering with ecologists, (ii) engaging with stakeholders, and (iii) valuing ecosystem services. On partnering with ecologists, the community would be well served by research that explicitly links critical zone science and services, interfacing as needed with the ecological community to draw on their advances and to identify complementary differences in emphasis. On engagement with stakeholders, the framework of critical zone services provides a common tool to learn more directly from managers, policymakers, and stakeholders what critical zone services are most important in different settings and how science can be most helpful in those contexts. For example, engaging with managers on how critical zone structure provides constraints to landscape response to short-term climate and ecosystem change, as well as rapid change associated with disturbances, will enable more effective management and valuation of ecosystem services. Regarding valuation of services, the community of critical zone scientists has a unique opportunity to engage with managers to conduct quantitative evaluation of services that derive from the coupling of biotic and geologic processes within the critical zone. Overall, advancing assessment of critical zone services represents a major, timely challenge. A critical zone perspective can expand the context, constraints, and currency of ecosystem services by providing an improved bridge between ecosystem services and the constraints thereon associated with critical zone processes. This framework can enable more effective management and valuation of ecosystem services, which is needed to respond to impacts of changing climate and associated disturbances.

Acknowledgments

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Table 1. Expanding context, constraints, and currency for ecosystem services by considering a critical zone perspective (modified from Costanza et al., 1997; Haygarth and Ritz, 2009).

<table>
<thead>
<tr>
<th>Service Type</th>
<th>Context</th>
<th>Constraints</th>
<th>Currency</th>
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<tbody>
<tr>
<td><strong>Provisioning Services</strong></td>
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<tr>
<td>Water storage</td>
<td>Expand focus on shorter-term water retention to include longer-term water retention and supply</td>
<td>Surface water storage is constrained by longer-term water retention (e.g., surface recharge to groundwater)</td>
<td>Water supply</td>
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<tr>
<td>Food supply</td>
<td>Expand current perspective on crop and livestock production to include provisioning source material</td>
<td>Crop and livestock production are constrained by soil productivity (e.g., topsoil, mineral, aggregates)</td>
<td>Food security</td>
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<td><strong>Habitat or Supporting Services</strong></td>
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<tr>
<td>Primary Production</td>
<td>Expand biological focus on plant productivity to include geophysical processes from soil to groundwater</td>
<td>Long-term primary production is constrained by rate-limiting processes in soil (e.g., soil genesis, fertility and erodibility)</td>
<td>Production of agricultural crops, bioenergy crops, timber, forage, and livestock</td>
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<tr>
<td>Soil Formation</td>
<td>Expand ecosystem-centered view to include longer geo-cognizant time scales</td>
<td>Rate of soil formation is constrained by longer-term geophysical processes (e.g., weathering of parent material)</td>
<td>Water storage and purification, nutrient storage, carbon sequestration</td>
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<td>Nutrient Cycling</td>
<td>Expand current framework to include longer-term storage and processing of nutrients</td>
<td>Nutrient cycling is constrained by biogeochemical processes in soil (e.g., mineralization and immobilization)</td>
<td>Supports primary production, helps prevent eutrophication</td>
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<td><strong>Regulating Services</strong></td>
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<td>Water quality regulation</td>
<td>Expand shorter-term focus to include longer time scales and deeper depths</td>
<td>Hydrological supply rates (e.g., groundwater supply)</td>
<td>Filtration and buffering</td>
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<tr>
<td>Water supply regulation</td>
<td>Expand focus on vegetation management to include more emphasis on soils and geology</td>
<td>Water supply management (e.g., irrigation, flood control)</td>
<td>Regulation of hydrological flows</td>
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<tr>
<td>Gas regulation</td>
<td>Expand shorter-term focus on plant and microbe responses to include longer time scale constraints</td>
<td>Greenhouse gas regulation (e.g., mineral weathering rates)</td>
<td>Regulation of atmospheric chemical composition</td>
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<td>Climate regulation</td>
<td>Explicitly incorporate geochemical controls on biologically mediated climate processes</td>
<td>Vegetation responses (e.g., respiration and photosynthesis) are constrained by biogeochemical processes (e.g., weathering and soil formation)</td>
<td>Regulation of global temperature, precipitation, and environmental processes</td>
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<td><strong>Cultural Services</strong></td>
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<td>Recreation</td>
<td>Expand ecotourism focus on biodiversity to include more geotourism focus on geological features</td>
<td>Geologic aesthetic value (e.g., Grand Canyon)</td>
<td>Providing a platform for recreational activity</td>
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<tr>
<td>Cognitive</td>
<td>Expand current perspectives related to biodiversity to include geological features</td>
<td>Educational and scientific value (e.g., Yellowstone)</td>
<td>Opportunities for noncommercial activities (e.g., aesthetics, education, and spiritual value)</td>
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References


