1-5-2015

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

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Recommended Citation

Field, J.P., Breshears, D.D., Law, D.J., Villegas, J.C., López-Hoffman, L. Brooks, P.D., Chorover, J., Barron-Gafford, G.A., Gallery, R.E., Litvak, M.E., Lybrand, R.A., McIntosh, J.C., Meixner, T., Niu, G.-Y., Papuga, S.A., Pelletier, J.D., Rasmussen, C.R., and P.A. Troch. (2015) Critical zone services: Expanding context, constraints, and currency beyond ecosystem services. Vadose Zone J. 14:1-7. https://doi.org/10.2136/vzj2014.10.0142

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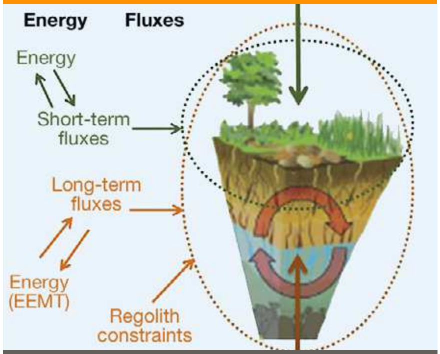
Priority Communications



Processes within the critical zone, such as soil formation, support and/or control many ecosystem processes and consequently the supply of products that benefits society. An expanded perspective of ecosystem services that encompasses the critical zone would enable more effective management and allow a more comprehensive valuation of services.

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Vadose Zone J.
doi:10.2136/vzj2014.10.0142
Received 9 Oct. 2014.
Accepted 20 Nov. 2014.
Open access

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5585 Guilford Rd., Madison, WI 53711 USA.

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 mass and energy are exchanged among the regolith, biosphere, and atmosphere (Lin, 2010; Lin et al., 2011; Chorover et al., 2011; Rasmussen et al., 2011). Processes within the critical zone, such as soil formation, hydrologic partitioning, streamflow generation, and landscape evolution support and/or control many ecosystem processes and, consequently, the supply of products that benefit 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 everything that an individual plant or animal needs to survive, including maintenance of genetic diversity; and (iv) *cultural services* consider recreational, educational, and aesthetic aspects (TEEB, 2010). These categories have been widely applied (deGroot et al., 2010; López-Hoffman et al., 2010; Watanabe and Ortega, 2011), although ongoing debate remains about how to best implement them under a variety of situations (Bateman et al., 2013a,b; Boyd et al., 2013; Obst et al., 2013).

A common challenge in evaluating and valuing ecosystem services is the convergence of ecosystem processes that occur at multiple spatial and temporal scales. Through incorporation of a critical zone perspective into this evaluation, ecosystem processes can be viewed as a complex function of mechanisms, including those extending deeper into the subsurface and farther back in geological time than is normally probed in ecology (noting though that prior climate and time gradient analyses have identified mechanistic linkages between substrate weathering and ecosystem processes; Chadwick et al., 1999; Vitousek et al., 2010). We believe that the concept of critical zone services can communicate the relevance of basic critical zone research to society for human well-being (Brantley et al., 2007; Banwart et al., 2011). This becomes particularly important as we use science to address growing societal needs in the face of increased population, landscape alteration, and climate change. Recent work has identified key linkages between ecosystem services and economic decision making (e.g., deGroot et al., 2010; Bateman et al., 2013a), and this framework has been further expanded to focus on soil services (van der Putten et al., 2004; Wardle et al., 2004; Haygarth and Ritz, 2009; Robinson et al., 2013). Insights obtained by focusing on soil services can be further expanded by considering a critical zone perspective. Most research on ecosystem services has been focused primarily on surface processes that depend on and are constrained by their interaction with subsurface critical zone processes (e.g., Dominati et al., 2010). Therefore, an improved bridge is needed between ecosystem services and the constraints thereon associated with critical zone processes. Because subsurface critical zone processes affect society, an expanded perspective of ecosystem services that encompasses the critical zone—*critical zone services* (Banwart et al., 2011, 2013; see also NSF Program Solicitation 12-575; http://www.nsf.gov/pubs/2012/nsf12575/nsf12575.htm, accessed 5 Dec. 2014)—would allow a more comprehensive valuation of services that benefit societal needs.

A critical zone perspective places different emphasis on services relative to an ecosystem perspective, such as relative consideration of geomorphological evolution of landscape vs. species distribution on the landscape, soil formation vs. soil constraints on plant growth, nutrient production vs. nutrient uptake, and carbon storage vs. carbon flux. In this paper we propose expansion of the scope of ecosystem services by specifying how critical zone processes (i) extend the *context* of ecosystem services spatially and temporally, (ii) determine *constraints* that limit rates of key ecosystem processes 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,

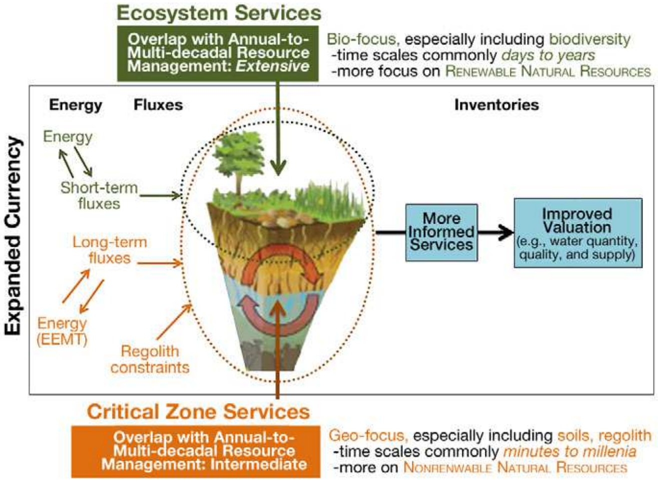

Fig. 1. Critical zone services provide context, constraints, and currency that enable more effective management and valuation of ecosystem services (adapted from MEA, 2005).

flood attenuation, and attenuation of pollutants (Banwart et al., 2013). Critical zone development occurs over longer time scales than ecosystem succession (Chadwick et al., 1999; Vitousek et al., 2003). For example, thousands to millions of years of interaction among organisms, water, gas, rock, and organic matter are required for the geomorphic production of a steady-state soil and biomass cover (Pelletier et al., 2013) and the formation of reactive interfaces (Chorover et al., 2007) that affect ecosystem carbon and water exchanges and the dynamics of stream chemical discharges (Perdrial et al., 2014). Just as critical zone science seeks to understand the subsurface weathering profile and its impact on regulating climate, nourishing ecosystems, and controlling water quality/quantity, critical zone services must be derived from biotic and geologic processes throughout that depth explored by freely circulating groundwater. The coupling of biotic and geologic processes within the critical zone produce "nonrenewable" (on human time scales) natural resources, such as soils, drainage networks, and groundwater flow systems. Expanding ecosystem dynamics in the context of critical zone processes will provide a more comprehensive understanding of fundamental processes that are critical for improved evaluation of ecosystem services.

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 "disservices," 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

This work was supported by the National Science Foundation for the Jemez River Basin–Santa Catalina Mountains Critical Zone Observatory (NSF-EAR-0724958 and NSF-EAR-1331408), with additional support from NSF EF-1340624 and the Arizona Ag Experiment Station. We especially thank other Jemez Mountain Basin–Santa Catalina Mountains Critical Zone Observatory team members for related discussion.

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).

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

References

Banwart, S., S.M. Bernasconi, J. Bloem, W. Blum, M. Brandao, S. Brantley, F. Chabaux, C. Duffy, P. Kram, G. Lair, L. Lundin, N. Nikolaidis, M. Novak, P. Panagos, K.V. Ragnarsdottir, B. Reynolds, S. Rousseva, P. de Ruitern, P. van Gaansn, W. van Riemsdijk, T. White, and B. Zhang. 2011. Soil processes and functions in critical zone observatories: Hypotheses and experimental design. Vadose Zone J. 10:974–987. doi:10.2136/vzj2010.0136

Banwart, S.A., J. Chorover, J. Gaillardet, D. Sparks, T. White, S. Anderson, A. Aufdenkampe, S. Bernasconi, S.L. Brantley, O. Chadwick, W.E. Dietrich, C. Duffy, M. Goldhaber, K. Lehnert, N.P. Nikolaidis, and K.V. Ragnarsdottir. 2013. Sustaining Earth's critical zone. Report of an International Workshop on Critical Zone Observatory Science. 9–11 Nov. University of Delaware, Newark. Available http://www.czen.org/files/czen/Sustaining-Earths-Critical-Zone_FINAL-290713.pdf.

Barbier, E.B. 2012. Progress and challenges in valuing coastal and marine ecosystem services. Rev. Environ. Econ. Policy 6:1–19.

Bateman, I.J., A.R. Harwood, G.M. Mace, R.T. Watson, D.J. Abson, B. Andrews, A. Binner, A. Crowe, B.H. Day, S. Dugdale, C. Fezzi, J. Foden, D. Hadley, R. Haines-Young, M. Hulme, A. Kontoleon, A.A. Lovett, P. Munday, U. Pascual, J. Paterson, G. Perino, A. Sen, G. Siriwardena, D. van Soest, and M. Termansen. 2013a. Bringing ecosystem services into economic decision making: Land use in the United Kingdom. Science 341:45–50.

Bateman, I.J., A.R. Harwood, G.M. Mace, R.T. Watson, D.J. Abson, B. Andrews, A. Binner, A. Crowe, B.H. Day, S. Dugdale, C. Fezzi, J. Foden, D. Hadley, R. Haines-Young, M. Hulme, A. Kontoleon, A.A. Lovett, P. Munday, U. Pascual, J. Paterson, G. Perino, A. Sen, G. Siriwardena, D. van Soest, and M. Termansen. 2013b. Ecosystem services: Response. Science 342:421–422.

Boyd, I.L., P.H. Freer-Smith, C.A. Gilligan, and H.C.J. Godfray. 2013. The consequence of tree pests and diseases for ecosystem services. Science 342:1235773 doi:10.1126/science.1235773.

Brantley, S.B., M.B. Godhaber, and K.V. Ragnarsdottir. 2007. Crossing disciplines and scales to understand the Critical Zone. Elements 3:307–314.

Breshears, D.D., L. López-Hoffman, and L.J. Graumlich. 2011. When ecosystem services crash: Preparing for big, fast, patch climate change. Ambio 40:256–263.

Broxton, P.D., P.A. Troch, and S.W. Lyon. 2009. On the role of aspect to quantify water transit times in small mountainous catchments. Water Resour. Res. 45. doi:10.1029/2008wr007438.

Chadwick, O.A., L.A. Derry, P.M. Vitousek, B.J. Huebert, and L.O. Hedin. 1999. Changing sources of nutrients during four million years of ecosystem development. Nature 397:491–497.

Chorover, J., R. Kretzschmar, F. Garcia-Pichel, and D.L. Sparks. 2007. Soil biogeochemical processes within the critical zone. Elements 3:321–326.

Chorover, J., P.A. Troch, C. Rasmussen, P. Brooks, J. Pelletier, D.D. Breshears, T. Huxman, K. Lohse, J. McIntosh, T. Meixner, S. Papuga, M. Schaap, M. Litvak, J. Perdrial, A. Harpold, and M. Durcik. 2011. How water, carbon, and energy drive critical zone evolution: The Jemez-Santa Catalina Critical Zone Observatory. Vadose Zone J. 10:884–899.

Costanza, R., R. d'Arge, R. de Groot, S. Farberk, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Suttonkk, and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. Nature 387:253–260.

DeFries, R., S. Pagiola, W.L. Adamowicz, H.R. Akçakaya, A. Arcenas, S. Babu, D. Balk, U. Confalonieri, W. Cramer, F. Falconí, S. Fritz, R. Green, E. Gutiérrez-Espeleta, K. Hamilton, R. Kane, J. Latham, E. Matthews, T. Ricketts, T.X. Yue. N. Ash, and J. Thönell. 2005. Analytical approaches for assessing ecosystem condition and human well-being. In: Ecosystems and human well-being. Current State and Trends: Findings of the Condition and Trends Working Group, Vol. 1. Island Press, Washington, DC. p. 37–71.

De Vries, J.J., and I. Simmers. 2002. Groundwater recharge: An overview of processes and challenges. Hydrogeol. J. 10:5–17.

deGroot, R.S., R. Alkemade, L. Braat, L. Hein, and L. Willemen. 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol. Complex. 7:260–272.

Dominati, E., M. Patterson, and A. Mackay. 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecol. Econ. 69:1858–1868.

Foley, J.A., R. DeFries, G.P. Asner, C. Barford, G. Bonan, S.R. Carpenter, F.S. Chapin, M.T. Coe, G.C. Daily, H.K. Gibbs, J.F. Helkowski, T. Holloway, E.A. Howard, C.J. Kucharik, C. Monfreda, J.A. Patz, I.C. Prentice, N. Ramankutty, and P.K. Snyder. 2005. Global consequences of land use. Science 309:570–574.

González-Pérez, J.A., F.J. González-Vila, G. Almendros, and H. Knicker. 2004. The effect of fire on soil organic matter– a review. Environ. Int. 30:855–870.

Graham, A., H. Ferrier, D. Mitchell, C. Jones, and P. Bicknell. 2013. Ecosystem services: The farmers' challenge. Science 342:420–421.

Green, T.R., M. Taniguchi, H. Kooi, J.J. Gurdak, D.M. Allen, K.M. Hiscock, H. Treidel, and A. Aureli. 2011. Beneath the surface of global change: Impacts of climate change on groundwater. J. Hydrol. 405:532–560.

Hall, C. 2004. Ecosystems and Energy: History and Overview. In: C.J. Cleveland, editor, Encyclopedia of energy. Vol. 2. Elsevier, Amsterdam. p. 141–155.

Havstad, K.M., D.P.C. Peters, R. Skaggs, J. Brown, B. Bestelmeyer, E. Fredrickson, J. Herrick, and J. Wright. 2007. Ecological services to and from rangelands of the United States. Ecol. Econ. 64:261–268.

Haygarth, P.M., and K. Ritz. 2009. The future of soils land use in the UK: Soil systems for the provision of land-based ecosystem services. Land Use Policy 26:S187–S197.

Heimsath, A.M., W.E. Dietrich, K. Nishiizumi, and R.C. Finkel. 1997. The soil production function and landscape equilibrium. Nature 388:358–361.

Kleidon, A., E. Zehe, and H. Lin. 2012. Thermodynamic limits of the critical zone and their relevance to hydropedology. In: H. Lin, editor, Hydropedology: Synergistic integration of soil science and hydrology. Academic Press, Walthman, MA. p. 243–281.

Lin, H. 2010. Earth's critical zone and hydropedology: Concepts, characteristics and advances. Hydrol. Earth Syst. Sci. 14:24–45.

Lin, H., J.W. Hopmans, and D.D. Richter. 2011. Interdisciplinary sciences in a global network of Critical Zone Observatories. Vadose Zone J. 10:781–785. doi:10.2136/vzj2011.0084

López-Hoffman, L., D.D. Breshears, C.D. Allen, and M.D. Miller. 2013. Key landscape ecology metrics for assessing climate change adaptation options: Rate of change and patchiness of impacts. Ecosphere 4. doi:10.1890/ES13-00118.1

López-Hoffman, L., R.G. Varady, K.W. Flessa, and P. Balvanera. 2010. Ecosystem services across borders: A framework for transboundary conservation policy. Front. Ecol. Environ 8:84–91.

Lyytimäki, J., L.K. Petersen, B. Normander, and P. Bezák. 2008. Nature as a nuisance? Ecosystem services and disservices to urban lifestyle. Environ. Sci. 5:161–172.

Lyytimäki, J., and M. Sipilä. 2009. Hopping on one leg—The challenge of ecosystem disservices for urban green management. Urban For. Urban Green. 8:309–315.

Mataix-Solera, J., A. Cerdà, V. Arcenegui, A. Jordán, and J.M. Zavala. 2011. Fire effects on soil aggregation: A review. Earth Sci. Rev. 109:44–60.

McGuire, K.J., and J.J. McDonnell. 2006. A review and evaluation of catchment transit time modeling. J. Hydrol. 330:543–563.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and human well-being: Synthesis. Island Press, Washington, DC.

National Research Council (NRC). 2001. Basic research opportunities in the earth sciences. National Academies Press, Washington, DC.

Obst, C., B. Edens, and L. Hein. 2013. Ecosystem services: Accounting standards. Science 342:420.

Odum, H.T. 1957. Trophic structure and productivity of Silver Springs, Florida. Ecol. Monogr. 27:55–112.

Orem, C., and J.D. Pelletier. 2015. The predominance of post-wildfire denudation in the long-term evolution of forested, mountainous landscapes. Proc. Natl. Acad. Sci. USA (in press).

Parks, S., and J. Gowdy. 2013. What have economists learned about valuing nature? A review essay. Ecosyst. Serv. 3:e1–e10.

Patterson, M. 1998. Commensuration and theories of value in ecological economics. Ecol. Econ. 25:105–125.

Perdrial, J.N., J. McIntosh, A. Harpold, P.D. Brooks, X. Zapata-Rios, J. Ray, T. Meixner, T. Kanduc, M. Litvak, P.A. Troch, and J. Chorover. 2014. Stream water carbon controls in seasonally snow-covered mountain catchments: Impact of inter-annual variability of water fluxes, catchment aspect and seasonal processes. Biogeochemistry 118:273–290.

Pelletier, J.D., G.A. Barron-Gafford, D.D. Breshears, P.D. Brooks, J. Chorover, M. Durcik, C.J. Harman, T.E. Huxman, K.A. Lohse, R. Lybrand, T. Meixner, J.C. McIntosh, S.A. Papuga, C. Rasmussen, M. Schaap, T.L. Swetnam, and P.A. Troch. 2013. Coevolution of nonlinear trends in vegetation, soils, and topography with elevation and slope aspect: A case study in the sky islands of southern Arizona. J. Geophys Res. Earth 118:741–758.

Rasmussen, C., P.A. Troch, J. Chorover, P. Brooks, J. Pelletier, and T.E. Huxman. 2011. An open system energy-based framework for predicting critical zone structure and function. Biogeochemistry 102:15–29 doi:10.1007/s10533-010-9476-8.

Riebe, C., W. Hahm, and S. Brantley. 2015. Going deep to quantify limits on weathering in the Critical Zone. Earth Surf. Process. Landf. (in press).

Robinson, D.A., N. Hockley, D.M. Cooper, B.A. Emmett, A.M. Keith, I. Lebron, B. Reynolds, E. Tipping, A.M. Tye, C.W. Watts, W.R. Whalley, H.I.J. Black, G.P. Warren, and J.S. Robinson. 2013. Natural capital and ecosystem services, developing an appropriate soils framework as a basis for valuation. Soil Biol. Biochem. 57:1023–1033.

Robinson, D.A., N. Hockley, E. Dominati, I. Lebron, K.M. Scow, B. Reynolds, B.A. Emmett, A.M. Keith, L.W. de Jonge, P. Schjønning, P. Moldrup, S.B. Jones, and M. Tuller. 2012. Natural capital, ecosystem services, and soil change: Why soil science must embrace an ecosystems approach. Vadose Zone J. 11. doi:10.2136/vzj2011.0051

Rockström, J., W. Steffen, K. Noone, Å. Persson, F.S. Chapin, III, E.F. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B.H. Walker, D. Liverman, K. Richardson, P. Crutzen, and J.A. Foley. 2009. A safe operating space for humanity. Nature 461:472–475.

Schröter, D., W. Cramer, R. Leemans, I.C. Prentice, M.B. Araujo, N.W. Arnell, A. Bondeau, H. Bugmann, T.R. Carter, C.A. Gracia, A.C. de la Vega-Leinert, M. Erhard, F. Ewert, M. Glendining, J.I. House, S. Kankaanpaa, R.J.T. Klein, S. Lavorel, M. Lindner, M.J. Metzger, J. Meyer, T.D. Mitchell, I. Reginster, M. Rounsevell, S. Sabate, S. Sitch, B. Smith, J. Smith, P. Smith, M.T. Sykes, K. Thonicke, W. Thuiller, G. Tuck, S. Zaehle, and B. Zierl. 2005. Ecosystem service supply and vulnerability to global change in Europe. Science 310:1333–1337.

TEEB. 2010. The economics of ecosystems and biodiversity: mainstreaming the economics of nature: A synthesis of the approach, conclusions and recommendations of TEEB. http://doc.teebweb.org/wp-content/uploads/Study%20and%20Reports/Reports/Synthesis%20report/TEEB%20Synthesis%20Report%202010.pdf (accessed 5 Dec. 2014)

Torn, M.S., S.E. Trumbore, O.A. Chadwick, P.M. Vitousek, and D.M. Hendricks. 1997. Mineral control of soil organic carbon storage and turnover. Nature 389:170–173.

USEPA. 2013. The importance of water to the U.S. Economy. MC 4101M Synthesis Rep. Office of Water, Washington, DC.

van der Putten, W.H., J.T. Anderson, R.D. Bardgett, V. Behan-Pelletier, D.E. Bignell, G.G. Brown, V.K. Brown, L. Brussaard, H.W. Hunt, P. Ineson, T.H. Jones, P. Lavelle, E.A. Paul, M.S. John, D.A. Wardle, T. Wojtowicz, and D.H. Wall. 2004. The sustainable delivery of goods and services provided by soil biota. In: D.H. Wall, editor, Sustaining biodiversity and ecosystem services in soils and sediments. Island Press, Washington, DC. p. 15–43.

Vitousek, P.M., O.A. Chadwick, G. Hilley, P.V. Kirch, and T.N. Ladefoged. 2010. Erosion, geological history, and indigenous agriculture: A tale of two valleys. Ecosystems 13:782–793.

Vitousek, P., O. Chadwick, P. Matson, S. Allison, L. Derry, L. Kettley, A. Luers, E. Mecking, V. Monastra, and S. Porder. 2003. Erosion and the rejuvenation of weathering-derived nutrient supply in an old tropical landscape. Ecosystems 6:762–772.

Vitousek, P.M., T.N. Ladefoged, P.V. Kirch, A.S. Hartshorn, M.W. Graves, S.C. Hotchkiss, S. Tuljapurkar, and O.A. Chadwick. 2004. Soils, agriculture, and society in precontact Hawaii. Science 304:1665–1669. doi:10.1126/science.1099619

Wardle, D.A., V.K. Brown, V. Behan-Pelletier, M.S. John, T. Wojtowicz, R.D. Bardgett, G.G. Brown, P. Ineson, P. Lavelle, W.H. van der Putten, J.M. Anderson, L. Brussaard, W.H. Hunt, E.A. Paul, and D.H. Wall. 2004. Vulnerability to global change of ecosystem goods and services driven by soil biota. In: D.H. Wall, editor, Sustaining biodiversity and ecosystem services in soils and sediments. Island Press, Washington, DC. p. 101–136.

Watanabe, M.D.B., and E. Ortega. 2011. Ecosystem services and biogeochemical cycles on a global scale: Valuation of water, carbon and nitrogen processes. Environ. Sci. Policy 14:594–604. doi:10.1016/j.envsci.2011.05.013

Wunder, S. 2005. Payments for environmental services: Some nuts and bolts. CIFOR Occasional paper 42. Center for International Forestry Research, Bogor, Indonesia.