



Perspectives: Critical zone perspectives for managing changing forests

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A B S T R A C T

Forest management is under intensifying ecological and societal pressures amid the current geological epoch, which some see becoming the Anthropocene. These pressures extend to temporal and physical scales typical of geology; however, integrating geological processes into forest management has lagged behind the inclusion of shorter-term and surficial ecosystem processes. As such, we examine the field of critical zone science for connections that translate geologic knowledge to forest management and planning. Earth's critical zone is the thin near-surface zone spanning from the bottom of circulating groundwater to the top of the atmospheric boundary layer of forest canopies. We explore four case studies from regions of the U.S.A. to highlight how recent critical zone discoveries inform contemporary forest management challenges. Some examples of management-relevant research include mediation of the impacts of climate change on forest productivity across gradients in geology, aspect, and topography; the role of bedrock water storage on drought resistance; hydrology-vegetation interactions following pest outbreaks; and quantification of water partitioning and erosion following fire. The accelerated pace of critical zone discovery has been synchronous with increased availability of open-source data resources for forest managers to expand this framework in management and planning.

1. Introduction

Forest management is rapidly changing amid significant environmental and societal shifts. Management paradigms have evolved from stand-level sustained wood yield approaches in the mid-twentieth century to encompass ecosystem-level processes and emergent properties (Polinko and Coupland 2021; Schober et al. 2018). Current trends in forestry emphasize multiple objectives to support a suite of ecosystem services across space and time (Polinko and Coupland 2021). Toward this end, forest managers are expanding approaches to continue meeting their goals during more severe drought and fires, changing water availability, and pest outbreaks. In this paper, we highlight how critical zone science may complement other approaches to forest management by emphasizing processes occurring over geologic timescales and at deeper depths below the land surface.

Critical zone science uses transdisciplinary environmental approaches to explore the thin near-surface zone spanning from the bottom of circulating groundwater to the top of the atmospheric boundary layer of forest canopies (U.S. National Research Council Committee, 2001). In 2007, funding from the National Science Foundation founded the Critical Zone Observatory (CZO) program at three sites across the U. S. By 2013, approximately 60 sites in 25 countries were identified as working in critical zone science (Banwart et al. 2013). Research in CZOs has shifted approaches to Earth surface processes into a highly collaborative and academically diverse arena (Brantley et al. 2017a). In forest

research, this has involved attempts to better incorporate geological structures and processes—by studying soils and waters to greater depths and across longer time scales—into conceptualizations of forests' structure and function. While critical zone processes occur across temporal scales, these longer geological scales may include processes occurring over millions of years. For example, mineral weathering and erosion are constraints on forest productivity that may result from millions of years of climatic cycles, while surface sediments were influenced over thousands of years during the most recent glacial period (Crowley and North 1991). Examples of this perspective have appeared throughout the past century of forestry science, such as research on the impacts of topography on forest composition and health (Whittaker and Niering 1964, 1965, 1968; Horsley et al. 2000) and the increasing role of topography in management (e.g., Hawthorne and Miniati 2018; Meigs et al. 2020). While forestry has long included these themes, the recent accelerated pace of critical zone science discovery and data availability (Table 1) represent a timely opportunity for a greater incorporation into forest management planning.

Our goal in this paper is to examine connections between critical zone science and forest management and illustrate cases where readily available critical zone data could augment forest management planning. To make these connections, we reviewed critical zone science related to forest management in the context of recent management plans for US National Forests in the same regions as Critical Zone Observatories. Our objectives are to (1) present a critical zone framework and how it may

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inform on ecosystem management; (2) highlight specific examples in which critical zone perspectives can support responses to contemporary forest management challenges; and, ultimately, (3) facilitate the expansion of critical zone concepts in forest management using nationally available data.

2. A general overview of the critical zone framework

Critical zone approaches frame forest ecosystems as a collective of relationships among the lithosphere, biosphere, and atmosphere (Fig. 1) and emphasize a scope of study that includes dynamics between the atmosphere, hydrosphere, and lithosphere. The outer crust of the Earth, the lithosphere, affects development of soil properties—such as soil depth, soil texture, nutrient availability, and water storage capacity (Hahm et al. 2014), which are the foundation for forests (Jenny 1941). In forests developing on bedrock or other rock-based parent materials, the zone where parent material meets biology is consequential for forest productivity; for example, bedrock structure determines the capacity of “rock moisture”, water in bedrock cracks and pores, that deep roots may tap to tolerate drought (Klos et al. 2018). Furthermore, the interaction between lithosphere and biosphere is not one-sided. Trees alter rock substrate through deep root networks (Roering et al. 2010; Hasenmueller et al. 2017), which promote physical and chemical weathering, as well as transport water and nutrients (Brantley et al. 2017a). Reciprocal relationships also exist between the atmosphere and lithosphere, with temperature, precipitation, and bedrock composition mediating weathering interactions (Clayton et al. 1979; Velbel 1985; Grantham and Velbel 1988; Velbel 1990).

Although climate constrains species ranges and productivity at coarse scales, elevation, aspect, and slope correlate with forest composition at finer scales relevant to forest management (Fricker et al. 2019). Various land stewards have used a general understanding of these links between topography and forest community type and development for over a century, including the Menominee nation in Wisconsin, who developed a sustainable forestry operation in the 1890s using ground vegetation as indicators for soil conditions and predictors for successful overstory species (Burgess 1996; Harkin 1983). Since then, several studies (Whittaker and Niering 1964, 1965, 1968; Kruckeberg 1986; Pregitzer and Barnes 1982) linked changes in geological features—such as elevation gradients—to changes in soil properties and the cascading influence on forest community development. Critical zone science has built on work describing these links to quantify the extent to which topography controls forest growth and incorporate these controls into models and maps at finer grains and larger spatial scales. For example, many case studies have linked local forest productivity to elevation (Fricker et al. 2019; Barnard et al. 2017; Swetnam et al. 2017), aspect (Barnard et al. 2017; Hinckley et al. 2014a; Hinckley et al. 2014b), and slope curvature (Perdrial et al. 2018; Smith et al. 2017). Critical zone

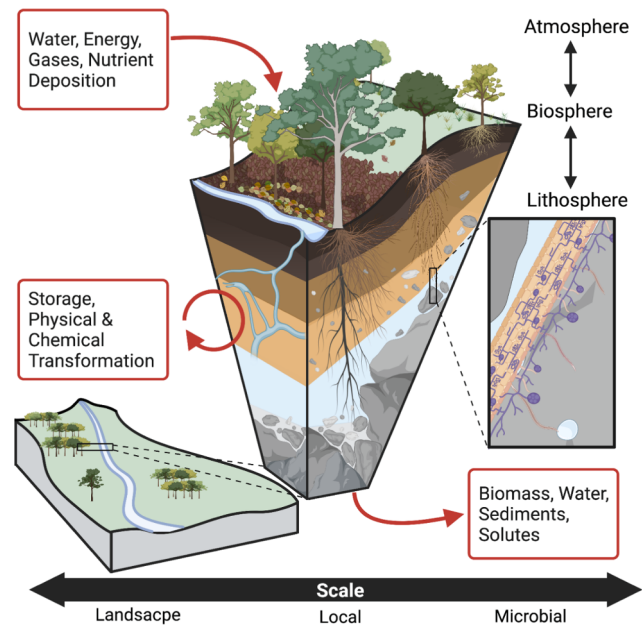


Fig. 1. The critical zone at nested scales from landscape to microscopic. Boxes represent inputs, internal cycles, and outputs between the lithosphere, biosphere, and atmosphere. Red arrows represent the movement of energy and mass. Figure modified from Rasmussen et al. (2011) and created with Bio-Render. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scientists have incorporated these known processes from local studies into coupled (hydrology-weathering-vegetation) critical zone evolution models to predict how bedrock weathering in forests might change under future climate (Sullivan et al. 2019). Translating relationships measured in one time and place into models spanning geological time and forest gradients offers a powerful approach to identify universal trends in the rate and movement of bedrock-derived nutrients to forests’ surface soils (Sullivan et al. 2019). This exemplifies how combining a history of conceptual work with critical zone science and data resources could augment the role of topography in forest management planning.

Critical zone science also emphasizes how material inputs into the atmosphere can travel across the globe and interact with local bedrock to influence forest productivity. A good example of this perspective comes from dust and acid rain research, much of which pre-dates the critical zone nomenclature. Atmospheric deposition, whether dry (e.g., dust) or wet (e.g., acid rain), can maintain productivity by replenishing nutrients and solutes depleted from bedrock (Derry and Chadwick 2007). However, forests downwind of nitrogen and sulfur emissions may

Table 1
Open-source critical zone data readily available to aid forest management.

Category	Data Source	Link
Bedrock	USGS, National Geologic Map Database UW-Madison, Macrostrat	https://www.usgs.gov/products/maps/overview https://macrostrat.org/
Soils	USDA, Web Soil Survey UC Davis, Soil Web	https://websoilsurvey.nrcs.usda.gov/ https://casoilresource.lawr.ucdavis.edu/gmap/
Vegetation	Multi-Resolution Land Characteristics (MRLC) Consortium National Park Service Vegetation Mapping	https://www.mrlc.gov/ https://www.nps.gov/im/vegetation-inventory.htm
Hydrology	USGS, National Hydrography USFWS, National Wetland Inventory	https://www.usgs.gov/core-science-systems/ngp/national-hydrography https://www.fws.gov/wetlands/
Human Population	U.S. Census Bureau	https://www.census.gov/data.html
Atmosphere	NOAA	https://www.noaa.gov/organization/information-technology/gis-in-noaa
Topography	OpenTopography USGS, National Map	https://opentopography.org/ https://www.usgs.gov/core-science-systems/national-geospatial-program/national-map
Imagery	USGS, Earth Explorer Google Earth Engine	https://earthexplorer.usgs.gov/ https://earthengine.google.com/
General Data	Cornell, GIS Library Guide	https://guides.library.cornell.edu/gis

experience acid precipitation that accelerates silicate weathering and depletes soil of base cations vital for plant growth, such as calcium (Ca). The rate and magnitude of this depletion links to bedrock composition, because tree roots or mycorrhizal fungi sometimes compensate for this loss through weathering of Ca-rich minerals (Blum et al. 2002; Green et al. 2013). Acid precipitation-induced Ca depletion has been problematic in northeastern US forests (e.g., Johnson and Siccama 1983), where it particularly limits red spruce (*Picea rubens* Sarg.) growth at mid-elevation (Engel et al. 2016). At higher elevations, climate and nutrient-poor soils limit tree growth, such that demand for Ca is low. However, alleviating Ca constraints on forest productivity, such as through liming, can create soil habitats preferred by non-native earthworms (Moore et al. 2015). The increased presence and abundance of non-native earthworms may have long-term consequences for forests' internal nutrient cycling (e.g., litter decomposition) and water outputs through enhanced soil porosity and evaporation (Moore et al. 2015). Overall, these examples demonstrate that critical zone perspectives recognize intricate interactions among forested systems, their underlying lithosphere and surrounding atmosphere (Brantley et al. 2017b).

3. How the critical zone framework expands on ecosystem management

Current forest management generally uses ecosystems-based approaches encompassing abiotic and biotic processes (Butler and Koontz 2005). An analysis of > 150,000 forestry documents found ecosystem-based trends emerging in and beyond the 1990s, with “ecosystem services” among the fastest growing trends in forestry today (Polinko and Coupland 2021). Similarly, a primary principle of the 1982 revision to the U.S. National Forest Management Act was “Recognition that the National Forests are ecosystems” (Department of Agriculture 1982), which permeates the most recent revision (Department of Agriculture 2012). Such systems thinking shows a shift toward more holistic approaches to management as compared to the prior emphasis on sustained wood yield at the scale of forest stands (Kaufmann et al. 1994).

However, the ecosystem paradigm has limitations (O'Neill 2001). For example, the need for spatially explicit and scalable methods led to landscape ecology as a distinct but complementary approach to enrich understandings of ecosystem structure and function (Lovett et al. 2005). Now another such expansion may aid in fully incorporating geological processes and properties into ecosystem approaches to forest management planning. The commonly measured belowground extent of ecosystems is often shallow, with most sampling limited to the top 30 cm of soils (Forest Inventory and Analysis National Program 2011; Richter and Billings 2015); yet deeper root, microbial, and geologic activity also influence forest processes. Further, forest ecosystems may be bound by geological time constraints, such as local limitations on the supply and delivery of water and essential nutrients from geologic and biologic processes (Field et al. 2015; Richardson and Kumar 2017). For example, soil genesis and associated nutrient supply and water storage capacity can occur on time scales of thousands to millions of years (Field et al. 2015). As such, spatiotemporal scales of typical ecosystem approaches might miss or under-represent the deeper and longer critical zone scales at play under complex and intensifying challenges of the 21st century.

In summary, an expansive view of the ecosystem concept can span the critical zone concept. Yet as they are typically practiced, critical zone science expands on the ecosystem concept by examining longer time scales and deeper hydrological, biological, and geological processes (Richter and Billings 2015; Richter et al. 2014).

4. Case studies of critical zone science in regional forest management

While the previous two sections introduced critical zone science, our intention is to connect these approaches to concrete applications in modern forestry. Here we highlight four key challenges to forest

management that critical zone approaches could help address: (1) climate change, (2) water scarcity, (3) pest and pathogens, and (4) fire. We discuss each challenge through examples from particular U.S. Forest Service (USFS) management regions. Although regional management plans encompass large areas, they reflect concerns emanating from the local- or even stand-level. These regions are an organizational framework to discuss issues at a broad scale of forest management. We recognize that each management challenge expands beyond one region, from small stands to globally, and we stress that critical zone perspectives are useful for all forms of forest management.

4.1. Climate change

Climate change influences forest productivity, and forest productivity is vital for climate change mitigation (Smith et al. 2014). Although climate change has indirect and varied impacts on forests, we highlight the direct effects of changing temperature and precipitation in the USFS East Region. In the past century, mean annual temperature increased 1.8–2.4°F across northeastern forests (Butler and Koontz 2018; Janowiak et al. 2018). Warmer climate may increase forest productivity with longer growing seasons and facilitate northern habitat expansion of species; however, such projections may be offset by more variable and severe weather (D'Orangeville et al. 2018; Smith et al. 2011). For example, despite a projected increase in precipitation, warmer and more extreme temperatures may decrease moisture availability if growing seasons lengthen (Allen et al. 2010; Clark et al. 2016). Since forest response to climate change is complex and often uncertain, delegating limited time and resources to manage for this challenge has not always been feasible. Some plans include objectives to monitor for indicators of climate change in their forest, such as snow loss (USDA Forest Service 2005) or changing growing season start and end dates (USDA Forest Service 2006). Other plans forgo explicit climate change objectives in favor of general maintenance of community biodiversity to increase resilience (USDA Forest Service 2007). However, foresters are working to proactively manage for climate change resilience and mitigation through initiatives such as the Climate Change Response Framework and Adaptive Silviculture for Climate Change (ASCC) experimental network (Nagel et al. 2017).

Climate-adaptive management could be informed by critical zone research linking forest growth to lithology and topography. The potential for lithology to influence the dynamics of Appalachian forests was documented nearly a century ago by naturalist E.L. Bruan (Braun 1935), with continued recognition by subsequent research (e.g., Nowacki and Abrams 1992); however, critical zone research has worked to quantify the influence of bedrock-mediated soil properties, such as water storage and nutrient availability, as constraints on forest distribution, diversity, and productivity (Hahm et al. 2014; Reed and Kaye 2020). In the mid-Atlantic Ridge and Valley province, shale-derived soils support forests with up to 20 % faster growth and 50 % greater carbon storage than those growing on sandstone (Reed and Kaye 2020), perhaps due to greater soil water availability (Marcon et al. 2021). Similarly, in the Connecticut River Valley, greater tree species richness is found on basalt bedrock relative to arkose, a coarse sandstone (Searcy et al. 2003). More diverse forest communities are expected to be more resilient to climate change in this region (Butler and Koontz 2018). As such, bedrock diversity could be a new criterion for site selection in future ASCC experimental designs (Nagel et al. 2017). Freely available bedrock maps from the US Geological Survey (Table 1) may help forest managers target bedrock properties to aid forest productivity goals and incorporate bedrock distribution into broader management planning.

Additionally, managers can use well-known topographic metrics—elevation, aspect, and slope curvature—to delineate areas for harvest and carbon sequestration. Foresters have long observed that aboveground productivity decreases with increasing elevation in the Appalachian Mountains (Bolstad et al. 2001). However, the structure of these hillslopes also influences carbon uptake and storage. In a

Pennsylvania watershed with complex terrain, more carbon was taken into wood annually along swale slopes relative to non-swale slopes, on southern aspects relative to northern, and along valleys relative to ridgetops (Smith et al. 2017; Brubaker et al. 2018). For forest harvesting operations, wetter swales and valleys may hinder machinery access, because warming winters shorten the time that soils are frozen (Butler and Koontz 2018). Shifting more intensive harvests to drier, upland forests may meet economic demands while preserving swales and valleys to sequester the most carbon on the least land area. The increasing availability of free remote sensing products, as well as predictive models linking these products to bedrock properties (Fraser et al. 2020), may help identify areas of convergent flow for targeted conservation and reforestation as climate refugia (Swanston et al. 2016). In short, broadening forest management paradigms to critical zone scales helps managers leverage bedrock and topography as tools to spatially prioritize conservation and harvesting in seemingly homogenous forests.

4.2. Water scarcity

Drought is a management concern with cascading effects: drought-stricken trees may succumb to pests and pathogens (Vose et al. 2016) while soils may release stored carbon (Blankinship and Schimel 2018). Drought is of increasing concern in western U.S. forests, where climate models project more precipitation “extremes,” such as droughts preceding floods (Swain et al. 2018). Research from the Southern Sierra and Eel River CZOs offers insight into how managers can use geology to identify areas primed to tolerate drought, and improve drought tolerance by strategically altering forest structure to increase snowpack accumulation.

Critical zone perspectives emphasize the role of geologic composition and structure in forest ecohydrology (e.g., Safeeq et al. 2021), which can help managers predict drought resilience. Although the presence of “rock moisture”—water trapped in weathered bedrock—has been recognized as a reservoir for deep tree roots (Graham et al. 1997), recent critical zone advances have quantified the magnitude and spatial extent of this water resource. For example, in an old growth forest in the Northern California Coast Range, trees accessed approximately four times more rock moisture than soil moisture during the dry season (Rempe and Dietrich 2018). In northern New Mexico, juniper (*Juniperus monosperma* (Engelm.) Sarg.) and piñon pine (*Pinus edulis* Engelm.) forests with access to rock moisture had increased resistance to drought and insect pests (McDowell et al. 2019). Extended drying of these reservoirs can induce widespread forest mortality, such as during California’s 2012–2015 drought (Goulden and Bales 2019). While recharge of rock moisture reservoirs depends on accumulation of winter precipitation, bedrock properties constrain water storage capacity: rock moisture accumulates to a site-specific maximum, above which additional precipitation quickly moves to groundwater (Rempe and Dietrich 2018). For instance, Hahm et al. (2019) find that deeply weathered argillite and sandstone in California’s Coastal Belt stores significantly more rock moisture for trees to access during summer than in the shallow-weathered Central Belt. Forest managers can use these bedrock-driven constraints on rock water storage capacity to diagnose and forecast forest response to droughts.

Mapping rock water storage capacity offers managers one approach to spatially prioritize practices that increase recharge, such as modifying the size and shape of canopy gaps to increase snowpack accumulation. In particular, the ratio between the measured diameter of the canopy gap compared with the height of the canopy surrounding the gap greatly impacts snowfall accumulation. Studies have found positive correlations with snowfall accumulation from gaps whose width is 1–3 times the canopy height (Varhola et al. 2010). Intermediate canopy gaps, whose width is 2–3 times the surrounding vegetation height (Golding and Swanson 1986), offer the best opportunity for elevated snowfall accumulation, as smaller gaps experience interception by neighboring vegetation and larger gaps experience wind exposure (Pomeroy et al.

2002; Varhola et al. 2010). Strategic cuttings reduce sublimation from the canopy, with more snow reaching the ground to melt and cycle through the forest (Harpold et al. 2020). Strategic gap creation can elicit benefits such as increased transpiration and elevated streamflow. Transpiration increases even under the driest scenarios, while streamflow recharge increases primarily during seasons with higher winter precipitation and subsequent snowmelt (Bart et al. 2021). Several western National Forests, including El Dorado (California), Tahoe (California), and Umatilla (Oregon and Washington), open canopy gaps to enable snowpack accumulation; however, more forests could benefit from this strategy under changing climate.

Geospatial databases (Table 1), such as the USDA Web Soil Survey, USGS National Geologic Map Database, and Multi-Resolution Land Characteristics Consortium, can aid in predictions of rock moisture storage based on soils, bedrock, and vegetation, respectively. These data can be paired with annual snowpack measurements from Snow Telemetry (SNOTEL) sites, daily snow cover fraction data (Naegeli et al. 2021), and northern hemisphere snow water equivalent datasets (Pulliainen et al. 2020). For these resources to retain and gain usefulness to forest management, collaborations are needed with groups collecting remote sensing and on-the-ground data to expand coverage and enhance accuracy. One such promising effort is the Snow Physics and LiDAR Mapping (SnowPALM) model, which uses LiDAR data on canopy height and vegetation density, along with weather and radiation, to predict snow accumulation and the corresponding water budget (Broxton et al. 2015; Harpold et al. 2020). As the accuracy of soil and geological data improves, our ability to proactively manage droughts will improve.

4.3. Pests and pathogens

Enduring bark beetle outbreaks in the Rocky Mountains call for analysis on the link between management of pest infestations and soil, water, and air quality (Rocky Mountain National Park 2005). Critical zone research, spearheaded by the Boulder Creek CZO and the USFS Fraser Experimental Forest in the Rocky Mountains, informs bark beetle management approaches implemented in three phases: prevention, suppression, and restoration (Samman and Logan 2000). Prevention involves preemptively lowering forest susceptibility to insect outbreaks, while suppression involves controlling existing outbreaks. Managers can leverage tools from critical zone science in both phases. For example, pine beetle infestation tends to establish and spread at xeric sites, because drought stress can increase susceptibility to attack (Raffa et al. 2008) and can reduce productivity post-attack (Knowles et al. 2017). Managers can find vulnerable xeric stands through data layers that identify water features linked to soil moisture and rock water capacity, such as perched aquifers and parent bedrock (Table 1). These sites may be targeted for treatment pre-outbreak or prioritized for salvage cuts amid outbreaks.

Critical zone science also offers insight into the restoration phase of beetle management. Restoration involves practices that increase forest resilience and may include returning ecosystems to pre-outbreak structure and function. One concern is whether forests will provide adequate downstream water quantity and quality after beetle-induced mortality (Rocky Mountain National Park 2005). While post-disturbance nutrient release varies widely in space and time, classical conceptual models anticipate an initial spike in streamflow and stream nutrient concentrations followed by a steep decline before a gradual return to baseline levels (e.g., Vitousek and Reiners 1975; Bormann and Likens 1979). However, recent research explores mechanisms that contradict these predicted responses due to complex critical zone interactions. For example, streamflow from forests in the Central Rocky Mountains showed no response to mountain pine beetle infestations, even when overstory infection reached nearly 80 % (Biederman et al. 2014). This lack of streamflow response can be explained by compensation in other hydrologic fluxes: abiotic evaporation increased (Biederman et al. 2014), and this effect may be greater on southern aspects (Rinehart et al.

2008). Further, a mortality event (>50 % canopy) in Fraser Experimental Forest induced no large increase in stream nitrate concentrations (Rhoades et al. 2013). Again, this lack of response is, in part, because of compensatory processes: new seedlings and small trees, which beetles do not prefer (Amman 1972; Safranyik and Vithayasai 1971), rapidly establish and increase nutrient uptake (Rhoades et al. 2013).

Synthesizing results from these two Rocky Mountain case studies illustrates critical zone processes that regulate stream water quality following outbreaks. Beetle killed upland soils can have high nitrate concentrations, and that nitrate may either be taken up locally by regenerating trees (or associated microbial communities) or transported to shallow groundwater and then downslope to the riparian zones (Biederman et al. 2014). There is evidence these processes vary with aspect and associated water balance (Biederman et al. 2014). These linkages among aspect, hillslope position, water balance, vegetation and nitrogen fluxes are relevant to salvage harvest planning, and especially the question of whether to salvage harvest in riparian zones. Harvesting riparian zones may be good for fuel reduction after beetle outbreaks, but only if the impacts on stream nitrate export are not large (as in Rhoades 2018). More generally, within and outside of riparian zones managers could stimulate seedling regeneration or supplement regeneration through plantings under beetle-opened canopies (USDA Forest Service 2011) to mitigate spikes in stream water nitrate.

4.4. Fire

Forest management plans often balance fire as an ecologically important process with protecting forests, property, and life from devastating wildfires (USDA Forest Service 2015; CalFire 2021). Fire forecasting and management have always been challenges at the nexus of soil, vegetation, atmospheric, and topographic feedbacks (Abdollahi et al. 2018; Busico et al. 2019; Eidenshink 2005; North et al. 2012; Preisler et al. 2009; Westerling 2016). Though environmental feedbacks associated with fire are too broad and complex to fully address here, critical zone scientists have continued the tradition of studying these feedbacks, with notable advances in the areas of post-fire water partitioning and quantifying fire impacts on geologic time scales.

Though much work has examined wildfire-induced changes in water discharge and evapotranspiration (Ma et al. 2020; Moody et al. 2008; Bart et al. 2021), critical zone approaches help quantify impacts of reduced post-wildfire vegetation on more uncertain water partitioning, such as groundwater storage and snow accumulation and melt (Bart and Tague 2017; Maina and Siirila-Woodburn 2020). For example, at the Catalina-Jemez CZO (New Mexico), post-fire vegetation loss led to ~10 % less water available for snow melt in burned areas, and fire caused the main control on water variability to shift from vegetation controls pre-fire to topographic controls post-fire (Harpold et al. 2014). Since topographic data are increasingly available at fine resolutions (e.g., Table 1), differences in elevation and aspect can be used to predict changes in water partitioning after fire and potential reductions in downstream water availability. Understanding how fire changes water routing through the critical zone may also help managers forecast water quality impacts. For example, post-fire increases in water flow through old mine workings drove elevated arsenic and metal concentrations in some forest streams of the Boulder Creek CZO (Colorado) (Murphy et al. 2020).

Fires of high intensity and long duration are known to deplete soil organic matter and cause sediment instability (Moody et al. 2013; Wieting et al. 2017), but critical zone researchers are expanding this work to geologic time scales by quantifying the importance of elevated post-wildfire erosion in landscape denudation across thousands to millions of years. For example, on the order of a few years, average post-wildfire erosion rates from a forest in Valles Caldera (New Mexico) were over 1000x higher than unburned watersheds of similar contributing area and geology (Orem and Pelletier 2016). Though these years of wildfire-affected erosion are relatively brief, across geologic time scales such moments account for at least 90 % of long-term denudation rates in

this forest (Orem and Pelletier 2016). As fires are increasing in size and severity, long-term sediment export from more forests may be controlled by wildfire. With these long-term trends in mind, post-fire recovery should be considered at time scales ranging from decades to centuries for forest regrowth to geological time scales for soil development and geomorphology.

5. Critical zone resources for forest managers

Moving forward, land management planning will likely continue leveraging increasingly holistic and interdisciplinary approaches. In our final section, we seek to facilitate the translation of critical zone science for interdisciplinary management planning by proposing strategies and highlighting resources for forest managers. A key opportunity is that data layers are becoming increasingly accessible tools for incorporating critical zone approaches into forest management.

Forest management includes diverse goals ranging from protection of vulnerable habitat and watersheds to recreation and timber production. For example, the U.S. National Forest Management Plans prioritize management for multiple uses and consider system drivers, such as dominant ecological processes, that allow ecosystems to adapt to change (Department of Agriculture 2012). The critical zone science examples we reviewed reflect just a subset of the ways that including long-term geologic and biologic processes as system drivers achieves integrated management goals. Some forest management plans already show leadership in this area by including sections focused on “geology” (e.g., Allegheny National Forest). However, these discussions can be limited to processes occurring in shallow soils, while discussions of bedrock tend to focus on the impacts of natural gas extraction (Thomas 1995) over impacts on forest ecology (Bailey et al. 2004). Managers recognize that deeper spatial and longer temporal processes are crucial to water and mineral storage, which impact survival and resilience of forest species to drought, fire, and pathogens; and critical zone science offers tools to infuse these processes into forest planning.

Many resources are freely available that managers can use to incorporate advances of critical zone science to enhance current forest management plans with deep space and time processes (Table 1). While some of these resources may be well known within forestry sub-disciplines, Table 1 offers a convenient compilation of such resources spanning the critical zone. For example, managers can use the USGS National Geologic Map Database to find patterns of bedrock diversity in seemingly homogenous landscapes (Section IV.1); use USDA Web Soil Survey maps to identify areas with increased resilience to drought (Section IV.2); use the National Insect and Disease Risk Map to prioritize restoration efforts (Section IV.3); and use OpenTopography to target drier locations for thinning to reduce fuel loads in fire-prone landscapes (Section IV.4). Additionally, imagery and ancillary data can provide private landowners with information on land-use legacies that may challenge management. Moreover, the increasing accessibility of remote sensing, big data, and computing abilities is rendering these tools the norm for effective management, making this an ideal time to incorporate critical zone advances into planning.

While foundational studies have laid the groundwork linking aboveground atmospheric and forest processes with soil, bedrock, and hydrological processes, critical zone science offers an opportunity to dive deeper by building a community of scientists and practitioners across specializations to co-analyze the larger system. New funding opportunities for a series of themes including bedrock and deep critical zone processes, dynamic water storage, and geomicrobiology/biogeochemistry presents a chance to purposefully introduce management for critical zone processes onto our national forests. In 2020, the original NSF-funded CZO Network evolved into the Critical Zone Collaborative Network and restructured their research approach from an observatory-centric model to a diverse collaborative network exploring critical zone concepts across academia, government, and privately-owned lands (CUASHI 2021). Critical zone scientists can leverage this chance to

better incorporate systematic study of deep geological processes into data collection in timber, watershed, soils, and game management that meets forest management goals. Land-use legacies are an example of a challenge ripe for cross-pollination between forest management needs and critical zone approaches. For example, Hauser et al. (2020) recently found that regenerating forests retain shallower rooting depths and different nutrient acquisition strategies than later successional forests after 60 + years of regrowth, even when aboveground biomass is comparable. Further exploring the persistence of anthropogenic legacies across soil depths and geological timescales is important for carbon storage, old growth conservation, and other management concerns ready to apply critical zone science. Overall, we highlight (1) principles of critical zone approaches, (2) four examples of how such approaches can inform contemporary forest management challenges, and (3) key resources as the foundation for collaborations with the new research networks. These make a compelling case for considering critical zone approaches in forest management planning.

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Data availability

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