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OPINION ARTICLE

Beyond traditional ecological restoration on the Colorado Plateau

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The Colorado Plateau is one of North America's five major deserts, encompassing 340,000 km^2 of the western United States, and offering many opportunities for restoration relevant to researchers and land managers in drylands around the globe. The Colorado Plateau is comprised of vast tracts of public land managed by local, state, and federal agencies that oversee a wide range of activities (e.g., mineral and energy extraction, livestock grazing, and recreation). About 75% of the Plateau is managed by federal and tribal agencies and tens of millions of people visit the Plateau's public lands each year. However, even in the face of this diverse use, our knowledge of effective ways to restore Plateau ecosystems remains relatively poor. Further, the multiple agencies on the Plateau have mandates that differ greatly in allowable practices, restoration needs, and desired outcomes. The Colorado Plateau is also expected to undergo ecosystem shifts in the face of climate change, further complicating management decisions and potentially limiting some options while creating others. Here, we explore the current state of Colorado Plateau restoration science and underscore key challenges and opportunities for improving our capacity to maintain the myriad of services provided by these desert ecosystems. We highlight past research efforts and future needs related to restoration concepts, including consideration and design of novel ecosystems, mitigation for and adaptation to climate change, use of genetically diverse seed adapted for current and future conditions, and the value of strong multi-agency and stakeholder collaborations in restoring systems on the Colorado Plateau and beyond.

Key words: desert, drylands, ecosystem services, local seed and plant materials, public land, socioeconomic values

Implications for Practice

- Dryland systems such as the Colorado Plateau present unique restoration challenges associated with low and variable precipitation, a limited mechanistic understanding of what drives outcomes in various land use contexts, and complexities and opportunities associated with multiple management agencies.
- A wealth of research has improved our understanding of managing resources in drylands, but relatively little research has occurred on the Colorado Plateau.
- Development of management options that increase restoration success could be particularly influential on the Colorado Plateau, as the dominance of public lands translates into opportunities for large-scale, coordinated restoration.
- Existing restoration programs on the Colorado Plateau highlight the value of multiagency and stakeholder collaborations in aligning restoration objectives and improving outcomes.

Restoration ecology has made substantial strides over the past few decades, with refined definitions, goals, and research strategies (Higgs et al. 2014). These steps forward include significant advances in defining and designing novel ecosystems

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(those with ecological assemblages or functions that differ from current or historical systems; Higgs 2017), as well as the study of historically ignored but globally relevant systems, such as drylands (Poulter et al. 2014). Restoration has also begun to incorporate climate change impacts in objectives and practice (e.g. Harris et al. 2006). One such system where restoration research and practices are rapidly developing is the Colorado Plateau. Here and in other drylands around the world, restoration is challenged by increasing aridity, evolving and intensifying land use, and dominance by invasive species (Milton & Dean 1995; Belnap et al. 2009; Steers & Allen 2010; Allred et al. 2015). These factors, coupled with the Colorado Plateau's unique climatic conditions and sensitivity to disturbance, may benefit from novel management and restoration techniques to prevent degradation of resources and damage to local economies (Aronson et al. 1993).

Need for Restoration Science on the Colorado Plateau

The Colorado Plateau is a large desert in the western United States, encompassing circa 340,000 km^2 (Fig. 1; an area more than 100 times larger than the state of Rhode Island and 9 times the size of Switzerland). The Colorado Plateau has several similarities, as well as important differences, with drylands across the globe. For example, the Colorado Plateau's dominant land owner is the American people, with well over three quarters of the Plateau being public land (i.e. federal, tribal, state; Fig. 1)—including lands open to grazing, recreation, and resource extraction (Copeland et al. 2017). This also includes extensive protected areas that have more stringent policies which limit the types of land use allowed (Schwinning et al. 2008). These public lands on the Colorado Plateau are attracting an ever-growing number of visitors, with tens of millions of visitors each year (Table S1, Supporting Information). Colorado Plateau ecosystems are not only vast and economically valuable, but also these ecosystems have notable biological value as well. The Plateau has the third highest number of endemic species across all taxonomic groups in North America, surpassing 109 other ecoregions (Ricketts et al. 1999). This wide biotic diversity is driven by the large abiotic gradients that occur on the Plateau (Fig. 1), with climates ranging from arid to dry subhumid, elevations ranging from 600 to 3,353 m, a wide range in geological substrates, and tremendous variation in soil types (Duniway et al. 2016). The Plateau also preserves high cultural value, both historic and modern, including archeological resources and language and cultural diversity (Nabhan et al. 2002). Maintaining such biological and cultural value in the face of rapid developmental growth provides a suite of information needs related to restoration.

While the Colorado Plateau is experiencing increasing land use intensity (especially oil and gas development; Copeland et al. 2017), our understanding of how to restore these ecosystems remains relatively poor. In addition to land use practices, climate change is affecting Colorado Plateau ecosystems and complicating responses to restoration efforts (Munson et al. 2011*a*). Thus, even for lands that are protected from particular types of disturbance, we know little about how the diversity and composition of these areas will respond to future climate conditions (but see Seager et al. 2007; Krause et al. 2015). This is an especially important consideration for the Colorado Plateau for two key reasons. First, the Plateau has a unique climatic regime, partially influenced by the North American monsoon, that interacts with heterogeneous geomorphic settings to affect water availability (Hereford & Webb 1992), oftentimes increasing restoration challenges. Second, many classes of Colorado Plateau biota are extremely sensitive to seemingly subtle changes in climate (e.g. Munson et al. 2011*a*; Reed et al. 2012; Wertin et al. 2015).

Interacting Factors Affecting Restoration Success

Colorado Plateau ecosystems will likely respond in unexpected ways to the interaction between increasing aridity and land use. The ecosystem consequences of these drivers could greatly impact regional economies that depend on public lands for ecosystem services like tourism revenue and water (Copeland et al. 2017). We expect that approaching restoration with a suite of tactics will be beneficial across Colorado Plateau ecosystems, where mosaics of vegetation types shaped by different environmental settings dot the landscape (Duniway et al. 2016). This environmental heterogeneity, including interactions among edaphic, biological, and climatic characteristics, may mean that restoration approaches that are successful in other drylands where annual and/or seasonal precipitation amounts are higher are not suitable for the Colorado Plateau. For example, restoration to remove the invasive tamarisk throughout the Southwest saw positive responses restoring native foliar cover in the Mojave and Chihuahuan deserts but no response on the Colorado Plateau (Harms & Hiebert 2006). Consequently, an approach that more specifically addresses the ecosystems and climate regimes of the Colorado Plateau may be necessary to achieve restoration success.

Restoration of native plant communities on the Colorado Plateau will not be achieved unless additional organisms beyond plants are considered. This includes preserving existing and restoring damaged biological soil crusts that are essential to rebuilding intact ecosystems here and in other systems around the globe (Munson et al. 2011*b*; Muñoz-Rojas et al. 2018). Biological soil crusts are a community of lichens, mosses, and/or cyanobacteria that play a host of roles in dryland systems (Belnap et al. 2016) and, until recently, represent a group of organisms for which our capacity to restore has traditionally been poor (e.g. Antoninka et al. 2018). In addition to stabilizing soil, maintaining surface hydrology, and mediating soil-atmosphere exchanges (Bowker et al. 2010; Darrouzet-Nardi et al. 2015; Faist et al. 2017; Torres-Cruz et al. 2018), biological soil crusts are influential in the structure and function of native plant communities as they increase plant germination rates, plant growth, and nutrient uptake (Harper & Belnap 2001; Su et al. 2007). For this reason, preserving biocrusted topsoil may be a particularly useful restoration technique on the Colorado Plateau and

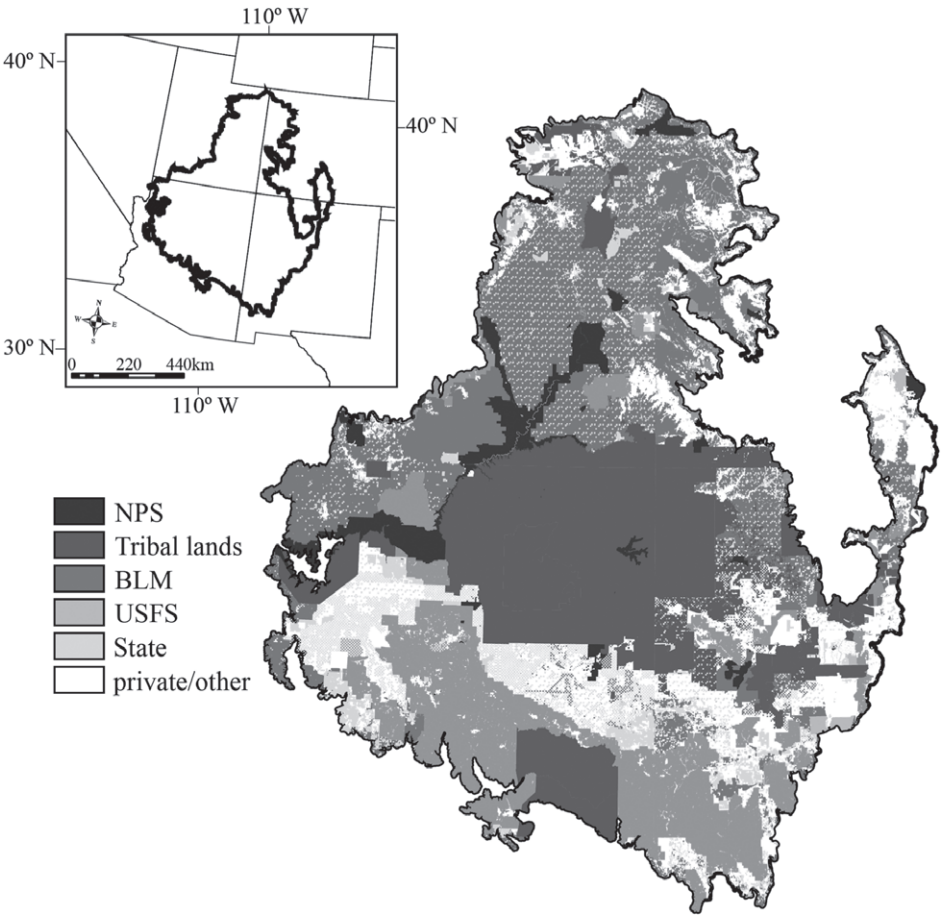

Figure 1. Map of the Colorado Plateau (inset) and of its land management boundaries. Ownership includes the National Park Service (NPS), Tribal lands, Bureau of Land Management (BLM), US Forest Service (USFS), state, county, and city lands (State), and private and all other ownership types. The upper left inset shows the location of the Colorado Plateau in the southwestern United States, spanning Colorado, Utah, New Mexico, and Arizona.

in other drylands; adding salvaged topsoil can enhance plant survival nearly as much as irrigation in drylands (Abella et al. 2015).

A more unified framework among agencies could encourage, inform, and support a range of restoration practitioners, leading to innovation on the Colorado Plateau (see Gellie et al. 2018 for a call for a global, unified, and standardized approach to restoration and McDonald et al. 2016 for implementation in Australia). Different agencies are guided by differing program goals and policy standards that may include which species, how much cover, and which ecosystem functions are desired in a restoration project (Shackelford et al. 2013), and thus could benefit from building upon differences and similarities to determine the best restoration options for specific needs and systems. For example, the National Park Service's mission for preservation and the Bureau of Land Management's mission for multiple uses may fundamentally differ but both agencies attempt similar restoration efforts aimed at keeping soils stable and native communities intact.

Identifying the best restoration options also involves identifying new technologies and addressing the projected future states of systems, as changing plant assemblages and ecosystem processes resulting from a changing climate will offer new challenges and, potentially, opportunities for restoration (Hulvey et al. 2017; Nauman et al. 2017). In practice, this is not an easy task as long-term postdisturbance and recovery data are often sparse, creating roadblocks to properly prepare for a changing climate, including increased climate extremes, when planning restoration projects (Reich & Lake 2015). Future climate scenarios reveal additional challenges for restoration, primarily determining which species should be planted where and when (Fernández & Morales 2016; Doherty et al. 2017). Paleoecological records indicate that vegetation communities over the past 10,000 years have responded to climatic variability similar to what communities experience today (Coats et al. 2008). Plant species on the Plateau are well-tuned to ephemeral and variable precipitation, but future projections of extremes outside the current range of variability suggests that we may not always be able to conserve or restore certain species if their ideal climate is no longer present (Bernstein et al. 2014; Richardson et al. 2014). Thus, prestoration, or utilizing species suitable for both current and future environments, has been proposed for selecting restoration species on the Colorado Plateau (Butterfield et al. 2017). Prestoration encourages restoration

practitioners to reconsider their desired outcomes and can potentially resolve conflicts in selecting target species for restoration, thereby potentially reducing costs and saving time and effort (Hobbs 2016).

One issue surrounding restoration is whether or not to use native plant seed. Non-native seeds have been used in the past due to evidence that certain non-native species are excellent at fast recovery and soil stabilization. However, the planting of non-natives can have ecosystem consequences that include altering community composition and nutrient cycling for decades following restoration (D'Antonio & Meyerson 2002), and the Bureau of Land Management and Forest Service have enacted policies over the past 20 years that encourage the use and development of native plant materials for the Colorado Plateau and much of the United States (Richards et al. 1998; Oldfield & Olwell 2015). Restoration ecologists have been subscribing to the theory-based idea that local seeds are the best sources for restoration projects, based on the assumption that such seeds are more adapted to local conditions than nonlocal sources (McKay et al. 2005; Johnson et al. 2010; Espeland & Kettenring 2018). However, under climate change, a greater understanding of microhabitat influences on populations, and the importance of capturing high genetic variation to prevent inbreeding depression has led many to declare that local seeds are not always best (e.g. Broadhurst et al. 2008). Additionally, the economic costs and low availability of native plant materials is often a direct limitation to their use (Peppin et al. 2010) and commercially available native cultivars can outperform local wild populations (Baer et al. 2014). However, the availability of regionally developed seed is minimal and the long-term influence of introducing cultivars into natural systems is poorly understood. As a result, demand for genetically diverse germplasm is increasingly met by strategically mixing populations to produce multisource seed lots (Broadhurst et al. 2008). This approach can make genetically diverse, appropriately adapted material available for large-scale production and restoration use (Weeks et al. 2011), but research is needed to understand how their use impacts restoration outcomes relative to other sourcing approaches.

A Way Forward

There has been some, although limited, restoration success on the Colorado Plateau, and these successes suggest potentially fruitful directions for restoration research and practice in these diverse ecosystems. Such successes include enhanced graminoid establishment once small-scale physical barriers were employed to intercept and collect resources (i.e., water, seeds, organic matter). This effectively allowed seeds to wait for ideal germination and establishment conditions while minimizing risk of soil erosion (Fick et al. 2016). Positive effects of seedbed modification on reclaimed gas pad sites in restoring native species and preventing invasive species establishment have also been reported (Eldridge et al. 2012). These successes are just the first step toward meeting future research and management goals. There remains a tremendous need to evaluate and synthesize past, unsuccessful practices applied on the Colorado Plateau, and remove them from the suite of restoration approaches while also attempting to scale small, site-level approaches to larger areas while addressing their cost-effectiveness and long-term impacts. Due to the inherent climatic variability of the Colorado Plateau in space and time, testing a restoration approach in multiple years or locations can enhance the specificity of restoration strategies (Vaughn & Young 2010).

Successful restoration of Colorado Plateau plant communities will most likely be achieved through sustained, strategic programs that include a combination of targeted and potentially evolving restoration practices, long-term monitoring and maintenance (coupled with adaptive management to allow for updating), landscape-scale collaboration, and a willingness to change traditional land management practices (Shinneman et al. 2008; Gellie et al. 2018). We propose a coordination of restoration efforts across large spatial scales and multiple land uses (similar to Utah's Watershed Restoration Initiative and the Bureau of Land Management's Colorado Plateau Native Plant Program; Wood et al. 2015; Clark et al. 2017), which can be a more cost-effective approach relative to small-scale projects (Neeson et al. 2015), especially as degradation and restoration needs cross administrative boundaries (Chambers & Wisdom 2009).

Restoration ecology is advancing quickly as our climate changes, and perceptions of desired ecosystem attributes and restoration goals change in tandem (Choi 2007; Martin 2017). Novel systems already exist as a result of the climate change and other direct and indirect human impacts (e.g. highly degraded lands with altered community composition and function, high-severity wildfire areas, and many restored areas themselves are novel; Hobbs et al. 2009), and understanding these systems and potentially utilizing them in restoration remains a challenge. This inherently includes synthesizing existing restoration knowledge to create new methods for managers and stakeholder groups to target restoration challenges specific to the Colorado Plateau. Although we remain hopeful, these challenges will likely make it increasingly difficult and, in some cases, impossible to restore systems to what they once were (Harris et al. 2006). That said, foundational and continued research on the impacts of multiple land uses and climate change on Colorado Plateau systems remain as pressing needs before managers can be expected to implement new restoration approaches. As a climatically vulnerable region predominantly managed by public agencies undergoing increasing pressure from varied interests, the way that restoration develops on the Colorado Plateau may determine what is to come elsewhere in the United States and abroad.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Visitation to National Park Service (NPS) Parks and Monuments on the Colorado Plateau in 2017 (NPS IRMA Data Store: https://irma.nps.gov/DataStore/).

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