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PRACTICAL ARTICLE

Improving restoration success through a precision restoration framework

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Dryland ecosystems represent a significant portion of global land area, support billions of people, and suffer high rates of land degradation. Successfully restoring native vegetation to degraded drylands is a global priority and major challenge—highlighting the need for more efficient and successful restoration strategies. We introduce the concept of "precision restoration," which targets critical biotic and abiotic barriers to restoration success and applies specific tools or methods based on barrier distribution in space and time. With an example from the sagebrush steppe biome, a North American cold desert, we present a framework for precision restoration in drylands that involves: (1) identifying site-specific critical barriers to restoration success, (2) understanding the spatial and temporal variability of each barrier, and (3) applying the best available restoration strategies given the specific barrier and its variability, described in the first two steps. This framework aims to enhance restoration success by focusing restoration practices on ameliorating the influential barriers when and where they occur and away from applying singular landscape-wide approaches.

Key words: drylands, restoration barriers, sagebrush steppe, seed enhancement technology

Implications for Practice

- Drylands account for a significant portion of the world's terrestrial surface and many are experiencing degradation at unprecedented levels. In addition to water limitation, stochastic and extreme weather conditions and invasive species present daunting challenges to restoring dryland landscapes.
- Conventional approaches often fail to meet the key goals of large-scale dryland restoration projects, such as rapid revegetation with native species.
- Precision restoration can improve outcomes by addressing critical barriers to plant establishment in dryland restoration with targeted techniques applied when and where barriers occur.

Introduction

Drylands account for approximately 40% of the global land area and support more than 1.5 billion people (Reynolds et al. 2007; Stavi & Lal 2015). Harsh environmental conditions make these systems highly susceptible to degradation, and up to 20% are considered to be severely degraded (Millennium Ecosystem Assessment 2005). While the fundamental need for ecological restoration of degraded ecosystems has been declared a major global priority by the United Nations, which proclaimed 2021–2030 a Decade on Ecosystem Restoration (United Nations General Assembly 2019), restoration success in many dryland regions remains severely limited (Kildisheva et al. 2016).

Drylands are characterized by episodic and infrequent occurrence of conditions that favor plant recruitment, which can significantly limit natural recovery following disturbance and thus require management intervention (Bainbridge 2007; Reynolds et al. 2007). Seed-based restoration is widely used and the most practical large-scale solution; however, in drylands it can often fall short of restoration goals, largely as a result of plant failure to overcome barriers to establishment (James et al. 2011; Kildisheva et al. 2016; Shriver et al. 2018). For example, widespread seedings after fire in the sagebrush steppe, a cold desert in the western United States, generally do not increase native plant cover when compared to unseeded burned areas (Knutson et al. 2014). This is likely a consequence of low survival across multiple demographic stages due to biotic and

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Box 1 Case study: Application to a model scenario in the sagebrush steppe biome.

Here we address an example of a restoration scenario, a large hypothetical postfire seeding on federal lands in Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp. *wyomingensis* Beetle & Young) steppe in the western United States. Across the 25,000 ha burn, much of the area suffered high fire severity with substantial loss of native perennial bunchgrasses and shrubs, and the invasive annual cheatgrass (*B. tectorum*) was already moderately abundant in major portions of the site. The management agency decided that active seed-based restoration was needed on 20,000 ha based on high value for wildlife and livestock forage, high fire severity, and higher density of cheatgrass and opted for natural regeneration on the remaining 5,000 ha that had lower fire severity and density of cheatgrass. The primary goal of seeding was to re-establish native perennial grasses and the keystone shrub, Wyoming big sagebrush, to accelerate recovery of livestock forage, wildlife habitat, and plant community resistance to cheatgrass. The burned area spanned a range of elevations, aspects, soil types, and invasive species abundance. To better demonstrate the utility of the precision restoration framework and the associated value of new and innovative restoration techniques, we will consider several in-development or recently proposed techniques as tools, despite their current unavailability for widespread use (Box 2).

Step 1: Are critical restoration barriers present?

Yes. Critical barriers include: *(1) competition from invasive annual grasses in low elevation areas with high prefire abundance, (2) hydrophobic soils in high-severity burn areas, and the likelihood of (3) potential hot and dry weather leading to drought stress, particularly at low elevations and warmer microclimates, like south-facing slopes*.

Step 2: Are the barriers variable in time and/or space?

Each of the three major barriers above is spatially variable (Table A1). Hot and dry weather conditions are temporally variable, but more severe at low elevations and on south-facing slopes, where they likely overlap with the invasive annual grass barrier.

Table A1. Barriers to large postfire seed-based restoration treatments in the sagebrush steppe for early plant life stages (germination through early post-emergence seedlings), mechanisms associated with these barriers, and their spatial and temporal variability.

Barrier	*Mechanism*	*Spatially Variable*	*Temporally Variable*
Post-germination freezing	Freezing following late autumn and/or winter germination kills seedlings	Yes, with elevation, latitude, and microsite	Yes, with weather, planting dates, and seed source traits
Post-germination desiccation	Drought conditions kill seedlings lacking deep roots or dormancy potential	Yes, with soil texture, elevation, and latitude	Yes, with weather and planting dates
Abundant invasive annual grasses	Seedlings outcompeted for resources by invasive species	Yes, with legacy and environmental factors	No, high abundance sites tend to remain high
Physical soil crusts	Seedlings killed by crusts forming over them	Yes, with soil texture	Yes, with weather relative to planting dates
Post-fire soil hydrophobicity	Dry conditions caused by reduced water infiltration kills seedlings	Yes, with burn severity, pre-burn vegetation, and soil factors	No, although effect declines over years

Step 3: Are predictions and/or maps available for major barriers?

Maps are available for pre-burn invasive annual grasses abundance as well as soil burn severity. Sufficiently accurate weather predictions for establishment conditions are not yet available at the time frame needed for management decisions related to seeding, since autumn seeding generally occurs months before crucial periods in seed germination, emergence, and establishment related to weather for most native perennial species. Maps of historical precipitation and temperature variation and averages could provide an estimate of the likelihood of dry and hot periods or freezing following favorable germination conditions across the treatment area.

Step 4: What restoration techniques are available to target these specific barriers?

A combination of both newer and traditional restoration techniques are considered. Hydrophobic soils will be addressed with a seed enhancement technology targeting that barrier, such as a surfactant-coated seed (Madsen et al. 2012*b*; Madsen et al. 2014*a*). Low-elevation areas with warmer microclimates, where early winter germination is possible, will benefit from the application of germination delay seed coating to reduce winter mortality of small seedlings postgermination (Madsen et al. 2016). If pre-emergent herbicide application for annual grass control is necessary, herbicide protection technology will be used to protect the seeded species from herbicide damage while herbicides control annual grass competition (Davies et al. 2017). Even if only standard seeding techniques are available, planning to repeat the seeding in consecutive years in areas with the highest risk of unfavorable conditions could also abate the risk of failure due to adverse weather during the establishment period (Wilson 2015; Davies et al. 2018).

Where a combination of barriers co-occur, such as both weather risk and invasive annual grasses, or where accurate barrier predictions are not available, a suite of restoration techniques will be applied. For example, the managers could include multiple treatments, such as seeding a mix of species or genotypes with both competitive traits and a range of climate associations (Leger et al. 2019), combining different levels of germination delay treatments targeting specific time windows (Madsen et al. 2016), and including herbicide protection pods in tandem with pre-emergent herbicide targeting exotic annual grasses (Davies et al. 2017; Clenet et al. 2019).

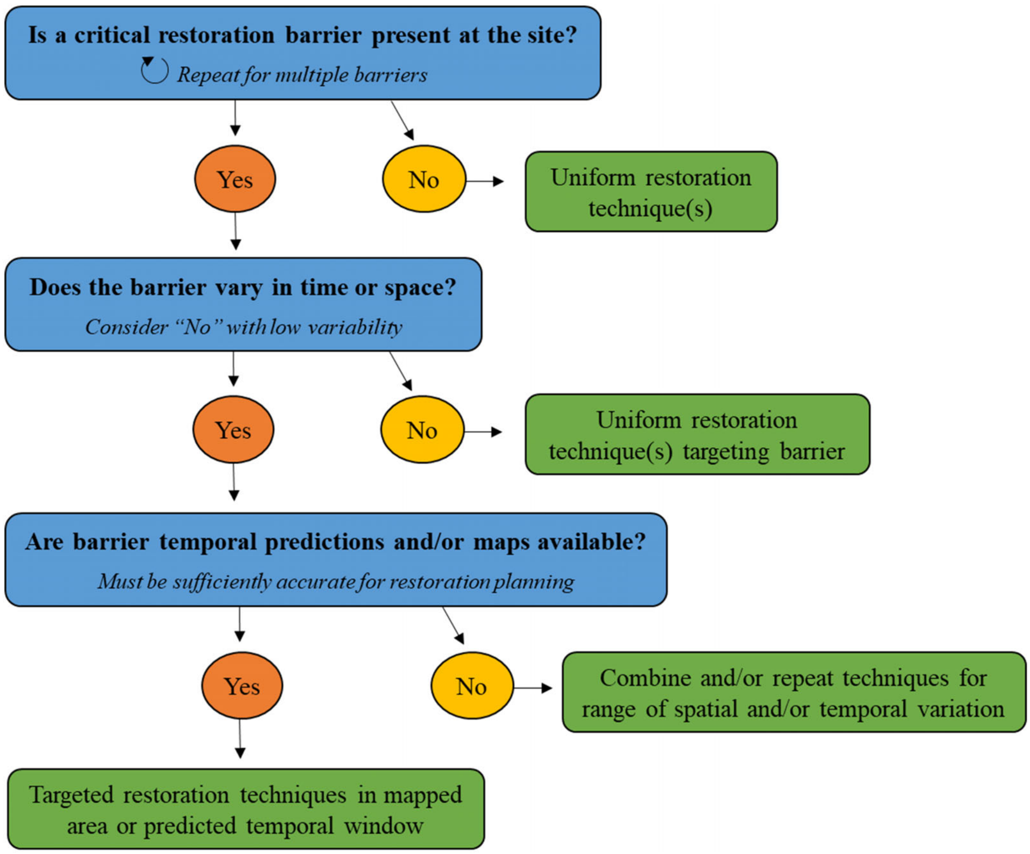

Figure 1. A precision restoration framework that aims to guide the selection and application of restoration techniques. This framework assumes that restoration is deemed necessary for the site prior to use. Steps of the framework rely upon practitioners to identify barriers and their potential spatial and temporal variability as well as availability of accurate predictions and maps for variable barriers. For sites with multiple restoration barriers, multiple iterations of the framework are needed to select techniques to apply in the specific areas where each barrier or set of barriers occurs.

abiotic barriers, from germination to established seedling stages (James et al. 2011).

Drylands are ecologically complex, with limited and variable abiotic conditions favoring plant recruitment. When these characteristics are combined with degradation, they become challenges to restoration that may require innovative solutions (Suding 2011). Those solutions that directly address critical causes of restoration failures within a given landscape are most likely to improve success. However, while new restoration techniques and predictive models to overcome key barriers in dryland systems are in development (Madsen et al. 2016; Hardegree et al. 2018), a framework to help guide the selection and application of these targeted methods is needed.

To address this need, we propose the adoption of "*precision restoration*," *defined as a framework for increasing restoration success by intentionally applying specific techniques to target the effects of known and variable ecological barriers encountered during restoration treatments*. Precision restoration contrasts with practices that do not consider the relative importance and spatial and temporal distribution of influential ecological barriers to restoration success and instead are uniformly applied across broad areas, often without consideration of temporal fluctuations in environmental conditions. We base this term on the well-established concept of precision agriculture (McBratney et al. 2005) that includes practices that rely on temporal and spatial targeting of key plant growth limitations to enable greater yield (e.g. applying fertilizer where needed, based on mapped nitrogen concentration, rather than opting for uniform application). There are three necessary conditions, described in detail below, for the precision restoration framework to be beneficial relative to traditional restoration methodologies: (1) the critical ecological barrier(s) to restoration are known, and addressing the barrier(s) will result in a meaningful increase in establishment of desired species, (2) techniques exist to ameliorate the effect of the barrier(s) on establishment, and (3) the occurrence of the barrier(s) in space and time can be sufficiently predicted to apply the selected techniques. Spatiotemporal barrier variability drives the need for a precision approach. If barriers were uniform, practitioners would employ the same restoration methodologies in all places and times without the need for appraising the spatial and temporal occurrence of specific limiting factors. However, given barrier variability, practitioners can optimize use of novel restoration techniques,

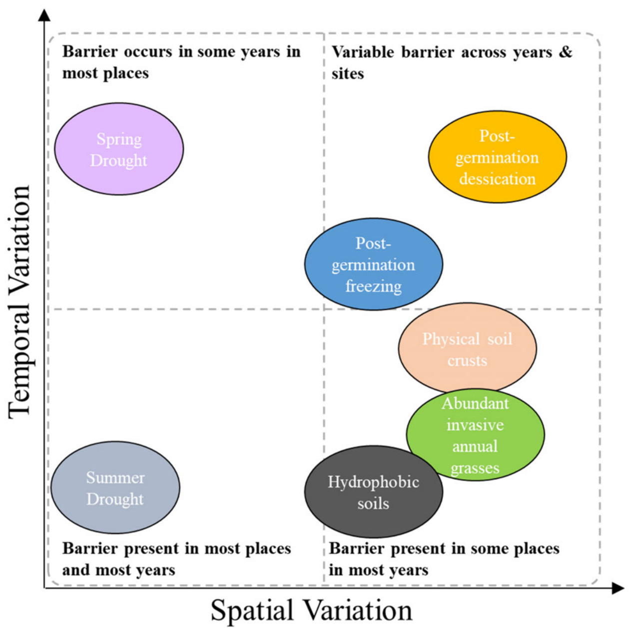

Figure 2. Illustration of barriers to restoration from seed in sagebrush steppe arranged by relative spatial and temporal variation based on the authors' opinion. Most barriers affect early life stages from germination to just after emergence (Box 2) whereas drought periods in spring and summer are more likely to affect older seedlings.

such as seed enhancement technologies (Pedrini et al. 2020) and trait-based seed source and species selection (Leger & Baughman 2015), as well as more traditionally used techniques (e.g. herbicide application, drill seeding, prescribed fire) along with geospatial mapping (Rinella & James 2017) and weather forecasting (Hagger et al. 2018) to strategically target these barriers in a cost-effective manner.

Precision restoration begins with the premise that a manager has already decided that restoration is necessary. Resource managers may opt to not actively restore in areas where natural regeneration or passive methods are likely to be successful or where restoration is likely to be prohibitively expensive (Hobbs et al. 2011). This decision-making process may benefit from considering the same barriers that limit restoration success. However, in general the decision whether or not to conduct active restoration, such as seeding, in a particular location may be complex and includes considerations not directly relevant to precision restoration (Holl & Aide 2011).

In this article, we use the sagebrush steppe biome as a focal system to describe how a precision restoration framework can improve planning and outcomes with a realistic scenario with seed-based restoration (Box 1). The sagebrush steppe is a cold desert plant community type that once spanned approximately 500,000 km^2 across western North America, primarily in the Great Basin region. Decline and degradation of sagebrush steppe affects numerous native species and ecosystem services. Over the last few decades conservation efforts have focused on habitat loss for sagebrush obligate bird species (Knick et al. 2003) such as the Greater Sage-grouse (*Centrocercus urophasianus*) and the emerging potential for accelerated ecosystem transformation with climate change (Abatzoglou & Kolden 2011; Schlaepfer et al. 2012). Numerous large-scale restoration treatments have been applied in response to an increase in large fires associated with positive feedbacks with non-native annual grasses, particularly cheatgrass (*Bromus tectorum* L., Balch et al. 2013).

We focus on seeding as a general restoration method because it is one of the principal tools for restoration in sagebrush steppe, particularly in response to wildfire. For instance, a compilation of decades of federal land management treatments in the Great Basin region, primarily in sagebrush steppe, showed that 300,000–350,000 ha are seeded per year in many years across hundreds of individual treatment areas (Pilliod et al. 2017). These treatments can be expensive; the seed cost alone for a recent 113,000 ha wildfire in the sagebrush steppe was 6.2 million USD (Soda Fire, Idaho/Oregon border, Bureau of Land Management 2016). Despite substantial financial, seed, and labor investment, restoration failures from seed are common, especially at lower elevations which tend to be affected by warmer and drier conditions and higher abundance of invasive species (Knutson et al. 2014; Pilliod et al. 2017; Shriver et al. 2018). However, in our region and well beyond, many other types of restoration treatments, from prescribed fire to grazing, could be approached in a similar manner as described here for seeding.

Identifying Critical Barriers to Success in Restoration Planning

As a first step in precision restoration, practitioners should consider whether a specific barrier, or barriers, to restoration exist on a given site (Fig. 1). For instance, in the sagebrush steppe biome, seed-based restoration can be limited by barriers including negative effects of extreme and variable weather, competition from invasive species, and soil characteristics affecting emergence and growth, such as soil hydrophobicity following wildfire (Table A1, Box 1). This can be a complex step in restoration planning efforts because practitioners may need to consider multiple barriers at different spatial and temporal scales. This process of identifying barriers does not need to be exhaustive, and instead should primarily focus on identifying and addressing the few most influential barriers.

A typical process for identifying critical barriers might involve listing the top potential barriers based on research or experience from seeding experiments or monitoring restoration treatments in areas with similar abiotic and biotic conditions in the region. These barriers should then be ranked in order of relative magnitude of impact on restoration success at a particular site, or portions of a site, and time. For example, in the sagebrush steppe biome, competition from invasive grasses is present in many areas, but their relative abundance and density differ spatially. The barrier of annual grasses may not rank highly in restoration planning at sites where their abundance is lower, whereas it would rank as a major barrier at sites with higher abundance.

Box 2 Barriers to restoration in the sagebrush steppe from Table 1 with techniques to address them, challenges and limitations of these techniques, and example references. Bolding indicates a seed enhancement technology and associated reference(s).

Barrier	*Restoration Technique Options*	*Challenges and Limitations*	*Example Reference(s)*
Post-germination freezing	Delay seeding until spring – typically requires a switch to broadcast seeding	Broadcast seeding is typically less successful than drill seeding	Boyd and Lemos (2015)
	Select seed sources adapted to restoration site climate	Few sources currently available due to historic lack of prioritization	Havens et al. (2015); Mummey et al. (2016)
	Delayed germination seed coatings	Unavailable for rangeland applications; uncertain applicability at large scale	**Madsen et al. (2018)**
Post-germination desiccation	Sagebrush transplants	Expensive compared to seedings for large areas	Davies et al. (2013); McAdoo et al. (2013)
	Winter or early spring seedings	Logistical challenges for drill seedings in areas inaccessible in winter	Boyd and James (2013); Boyd and Lemos (2015)
	Select seed sources with early establishment traits	Few sources currently available due to historic lack of prioritization	Larson et al. (2015); Leger et al. (2019)
	Seed priming for rapid germination	Unavailable for rangeland applications; treatments may vary by species/sources	**Hardegree (1996); Paparella et al. (2015)**
Abundant invasive annual grasses	Pre-emergent herbicide; delay seeding by 1 year to avoid herbicide toxicity	Competition from invasives increases as herbicide toxicity declines	Davies (2010)
	Low herbicide rate and immediate seeding (single-pass system)	Difficult trade-off with lower herbicide efficacy and effects on seeded species	Sheley et al. (2012*a*, 2012*b*)
	Select seed sources with tolerance to higher competition	Few sources currently available due to historic lack of prioritization	Ferguson et al. (2015); Leger et al. (2019)
	Seed into areas with large-scale cheatgrass die-off from pathogens	Unpredictable timing and scale of die-off events	Baughman et al. (2017); Weisberg et al. (2017)
	Herbicide protection seed technology with pre-emergent herbicide	Unavailable for commercial production; unproven at large scales	**Madsen et al. (2014*b*); Clenet et al. (2019)**
Physical soil crust	**Seed agglomerates**	Research needed on incidence and impact of barrier in natural systems	**Madsen et al. (2012a); Larson et al. (2019)**
Post-fire soil hydrophobicity	**Surfactant-coated seeds**	Research needed on incidence and impact of barrier in natural systems	**Madsen et al. (2012b); Madsen et al. (2014a)**

Anticipating Spatial and Temporal Variation in Barriers in Restoration Planning

Variability in restoration barriers is a key element in deciding which technique(s) to employ in specific areas and years. Some barriers may be consistently present across years and/or in the same locations, whereas others may vary significantly across space and time (Table 1, Fig. 2). Failing to consider variability in restoration planning could lead to unsuitable treatments with low success; conversely, optimizing the combination of treatments based on environmental variation can improve cost-efficiency (Kimball et al. 2015).

Considering the relative importance of spatial and temporal variation for the target restoration project may also affect planning. For example, for large-scale restoration projects (e.g. hundreds or thousands of hectares), the spatial variation of environmental gradients associated with barriers to seedling establishment (i.e. elevation, topographic microclimate, and soil type) could be high (Fig. 1 in Svejcar et al. 2017). Conversely, temporal variation of barriers may be more influential than spatial variation for smaller projects with a narrower range of strong environmental gradients.

Incorporating weather forecasts into a precision restoration framework could be highly effective for addressing weather-related barriers to plant establishment (Bradford et al. 2018; Hardegree et al. 2018). For example, in the sagebrush steppe biome, drill-seeding generally occurs in autumn due to frozen winter soils and spring mud limiting access, yet freezing-induced mortality of autumn germinated seed can be a barrier to restoration success (Boyd & Lemos 2013). Where and when this barrier occurs, seed enhancement technology for delayed germination could decrease high winter mortality rates with autumn seedings (Richardson et al. 2019).

Though potentially highly useful for precision restoration, accurate medium- to long-term weather predictions are not currently widely available for many weather-related barriers and sites, though they are on the horizon (i.e. Hagger et al. 2018). Even if predictions are lacking, historical weather data could be used to provide a probabilistic estimate of likely weather-related conditions that could still be used to guide restoration planning. For instance, an assemblage of germination timing seed enhancements (e.g. to induce, speed up, and/or slow down germination) could be combined to target the range of favorable conditions or the site could be seeded multiple times to increase the likelihood of encountering favorable conditions.

Discussion

The global scale of the arid land restoration challenge due to ongoing degradation is daunting (Stavi & Lal 2015) and will require efficient, broad-scale restoration techniques (Suding 2011). Nonetheless, recent and near horizon advances in science, policy, and practice for dryland restoration could be leveraged to meet this challenge. We suggest that using the precision restoration framework to more efficiently apply standard restoration approaches and/or newly developed approaches to address specific barriers will improve outcomes and reduce costly failures – particularly in arid lands, where opportunities for restoration success are limited.

Embracing a precision restoration framework is particularly important for the strategic development and/or efficient use of restoration techniques, such as seed enhancement technologies, that target specific barriers. Precision restoration places emphasis on advancing research to identify key barriers, a critical step needed to develop innovative techniques to target these barriers. For example, links between weather variables and the survival and growth of sagebrush steppe species at specific life stages (i.e. germination to emergence) have only recently been documented (e.g. James et al. 2011), yet this research immediately spurred development of a host of promising, targeted techniques (Madsen et al. 2016). Furthermore, the use of highly targeted techniques such as seed enhancement technologies in the absence of a clear understanding of barrier presence across space and time is likely to waste resources, fail to demonstrate their true value in the correct context, and result in underwhelming support for their use.

In some cases, restoration techniques for targeting a critical barrier may be unavailable, prohibitively expensive, or logistically unfeasible. Several approaches and technologies targeting critical restoration barriers are at various stages of development (Box 2), and therefore not yet widely available to use. In systems other than our example, the sagebrush steppe, no specific techniques may be available for targeting the most significant barriers to restoration. Whether increases in success with precision restoration will be worth additional costs or implementation effort may depend on a number of project-specific factors. For instance, a potentially higher cost of using the precision restoration framework may be warranted for a highly valuable species or ecosystem. In circumstances where the success rate of conventional approaches is unacceptably low, a more expensive precision restoration approach may be preferable, even if the trade-off with the higher cost is a reduction in the restoration area. Techniques useful for precision restoration should be developed to align with typical restoration practices and equipment if possible, but they may also require special considerations that limit their use in some circumstances. For instance, novel approaches like seed coatings that are designed to control germination timing or offer herbicide protection may be compatible with existing drill seeding equipment, but limited by the need for timely seeding relative to herbicide application or desired spring germination windows. However, identifying major barriers may be useful even if precision restoration is not an acceptable or currently available approach, because the process could still guide restoration planning or suggest research into additional methods. For example, a practitioner may decide against wasting resources with a more conventional restoration treatment if it will not address a major critical barrier to success (Kimball et al. 2015).

Overall, the precision restoration framework guides practitioners and researchers through a series of steps to select and/or develop targeted techniques for improving restoration outcomes, particularly in areas with challenging environmental conditions for plant establishment, such as drylands. Broadly the framework calls for identifying key barriers to seedling establishment with restoration, describing the associated timing and geospatial variability of the barriers, and selecting appropriate restoration techniques for a particular time or place. This approach has the potential to improve the success and cost-effectiveness of dryland restoration by focusing restoration and research efforts on linking the spatial and temporal variability of barriers to plant restoration with existing or novel techniques to overcome these barriers.

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