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Weather-Centric Rangeland Revegetation Planning☆

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ABSTRACT

Invasive annual weeds negatively impact ecosystem services and pose a major conservation threat on semiarid rangelands throughout the western United States. Rehabilitation of these rangelands is challenging due to interannual climate and subseasonal weather variability that impacts seed germination, seedling survival and establishment, annual weed dynamics, wildfire frequency, and soil stability. Rehabilitation and restoration outcomes could be improved by adopting a weather-centric approach that uses the full spectrum of available site-specific weather information from historical observations, seasonal climate forecasts, and climate-change projections. Climate data can be used retrospectively to interpret success or failure of past seedings by describing seasonal and longer-term patterns of environmental variability subsequent to planting. A more detailed evaluation of weather impacts on site conditions may yield more flexible adaptive-management strategies for rangeland restoration and rehabilitation, as well as provide estimates of transition probabilities between desirable and undesirable vegetation states. Skillful seasonal climate forecasts could greatly improve the cost efficiency of management treatments by limiting revegetation activities to time periods where forecasts suggest higher probabilities of successful seedling establishment. Climate-change projections are key to the application of current environmental models for development of mitigation and adaptation strategies and for management practices that require a multidecadal planning horizon. Adoption of new weather technology will require collaboration between land managers and revegetation specialists and modifications to the way we currently plan and conduct rangeland rehabilitation and restoration in the Intermountain West.

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Introduction

Millions of hectares of rangeland in the western United States are either currently degraded or under threat of degradation from the influence of invasive annual grasses (D'Antonio and Vitousek, 1992; Knapp, 1996; Bradley and Mustard, 2006; Davies, 2008, 2010; Bromberg et al., 2011; Brooks et al., 2016; Germino et al., 2016). These invasive species are particularly well adapted to western rangeland environments that experience high variability in annual and seasonal precipitation and temperature. Some useful weather-adaptive traits of these species include prolific seed production, rapid establishment response to short periods of site availability, rapid growth, preemptive utilization of site resources, and an annual life cycle that facilitates survival during seasonal drought (Harris, 1977; Melgoza et al., 1990; Reichenberger and Pyke, 1990; Arredondo et al., 1998; Humphrey and Schupp, 2001, 2004; Kulmatiski et al., 2006; Rimer and Evans, 2006; Hardegree et al., 2010, 2013; Mangla et al., 2011; Mazzola et al., 2011). Annual grass proliferation also results in significant and self-perpetuating changes to nutrient cycling, fire frequency, and vulnerability

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to postfire wind erosion that reinforce site dominance and prevent reestablishment of desirable perennial species (Norton et al., 2004; Bradley et al., 2006; Boxell and Drohan, 2009; Rau et al., 2011; Balch et al., 2013; Blank et al., 2013; Gasch et al., 2013; Owen et al., 2013; Germino et al., 2016). Landscape-level transitions to annual-weed dominated plant communities have had major negative environmental and economic impacts on natural resource values, land management costs, and societal benefits from western rangelands (Riggs et al., 2001; Duncan et al., 2004; Epanchin-Niell et al., 2009; Brunson and Tanaka, 2011; Maher et al., 2013).

Western rangelands are heterogeneous for a wide range of biophysical characteristics. The western United States generally has complex topography and soil variability at scales typically smaller than boundaries associated with management applications (Herrick et al., 2006; Bestelmeyer et al., 2011). Relatively detailed site information is now available, or under active development, from the Natural Resources Conservation Service (NRCS) as ecological site descriptions (ESDs) and associated state-and-transition models (STMs; Herrick et al., 2006; Caudle et al., 2013; NRCS, 2013). Site-specific information on potential weather effects on vegetation is usually limited to the identification of plant materials that are associated with broad climatic zones (Shiflet, 1994; Vogel et al., 2005; NRCS, 2006; Bower et al., 2014). Recent research, however, has identified climatic gradients of precipitation and temperature that are associated with both the relative difficulty of seedling establishment and the inherent resistance and resilience of mature plant communities (Chambers et al., 2014b; Knutson et al., 2014).

Historically, the predominant management response to invasive annual weeds has been postfire seeding under federal agency Emergency Stabilization and Rehabilitation (ESR) programs (Eiswerth and Shonkwiler, 2006; USDI BLM, 2007; Eiswerth et al., 2009; Pyke et al., 2013; Knutson et al., 2014). ESR plans are mandated for rapid implementation in the years immediately following the fire, emphasize site and soil stabilization, and have not been integrated with longer-term interventions necessary to sustain a positive trajectory toward an acceptable vegetation state (USDI BLM, 2007; USDI, 2015). Short-term, postfire rehabilitation management also restricts initial establishment success to the relatively low probability of favorable weather in the years immediately following disturbance. Pyke et al. (2013) conducted a meta-analysis to determine whether seeding after wildfires has reduced invasion or abundance of undesirable non-native plant species and found that the majority of postfire seedings (67%) had no effect. Overall success rates tend to be greater at higher elevation, where climatic conditions are generally more favorable for establishment (Davies et al., 2014; Knutson et al., 2014), but initial establishment success at drier sites is still possible with adequate precipitation in the winter and spring (Jessop and Anderson, 2007; Taylor et al., 2014).

The objective of this synthesis is to provide a framework for incorporating weather and climate information into rangeland revegetation planning: to reduce management uncertainty, to improve our understanding of the ecological processes driving succession, and to increase the efficiency of rangeland rehabilitation and restoration efforts.

Weather Variability and Plant Establishment

The microclimatic requirements for many successional processes and life-stage transitions are much more restrictive than those necessary for the persistence of mature plant communities, even in the absence of competitive annual weeds (Grubb, 1977; Call and Roundy, 1991; Peters, 2000; Hardegree et al., 2003, 2013, 2016; Cox and Anderson, 2004). In particular, transition pathways between undesirable and desirable plant-community states may require a series of specific, and, therefore, infrequent weather patterns to sustain a positive successional trajectory through multiple phases of plant community development (Fig. 1; Westoby et al., 1989; Call and Roundy, 1991; Hardegree et al., 2011; James et al., 2011, 2013; Svejcar et al., 2014).

Weather Impacts: Examples from the Literature

An example of the importance of weather in the phenological timing of germination and root growth comes from efforts to improve establishment of native grasses at the Santa Rita Experimental Range in southern Arizona. Average annual temperature in this area is 17.7°, and average precipitation is about 400 mm, with about half falling during the summer monsoon period. Warm season grasses have traditionally been sown during the spring before the onset of monsoonal moisture. Years of field research indicated that Lehmann lovegrass (*Eragrostis lehmanniana* Nees) and other introduced South African grasses establish more successfully than native grasses (Roundy and Biedenbender, 1995). In a comparative study, Abbott and Roundy (2003) found that the majority of native grass seeds germinate relatively quickly after the onset of summer thunderstorms, whereas a relatively small fraction of Lehmann lovegrass seeds germinate during any particular period of water availability (Hardegree and Emmerich, 1991, 1993; Roundy et al., 1992). Without a consistent period of subsequent water availability, seminal root growth cannot keep up with the soil drying front, adventitious roots do not develop, and seedlings become highly vulnerable to desiccation and detachment (Tischler and Voigt, 1987; Roundy et al., 1993, 1997; Abbott, 1999). The success of Lehmann lovegrass is partially attributed to reserving some seed cohorts to germinate later in the monsoon season when precipitation frequency and soil moisture increase (Roundy et al., 1996). Incorporating site-specific information on the seasonality of precipitation frequency as it pertains to establishment probability has led to the recommendation that establishment of native grasses could be improved by seeding later in the summer.

In another example of weather-dependent life-cycle transitions, studies have shown that germination is generally not limiting, regardless of planting date, but there is often a large discrepancy between germination and emergence in the field for fall-planted perennial grasses in the Great Basin (Hardegree and Van Vactor, 2000; Roundy et al., 2007; James et al., 2011; Boyd and Lemos, 2013). The relative timing of germination, however, can be extremely important as pre-emergent seedlings are vulnerable to relatively short periods of soil freezing and/or soil desiccation (James et al., 2011; Boyd and Lemos,

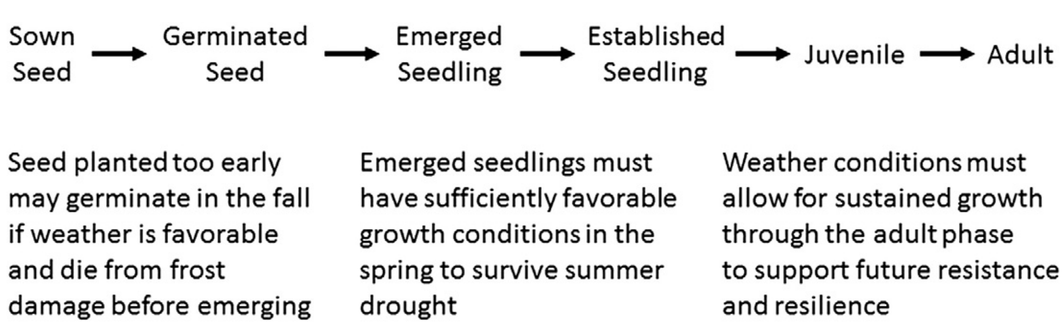

Figure 1. Life stage transitions (from James et al., 2011) and weather effects on growth and mortality of seeded grass and shrub species.

2013; Hardegree et al., 2016; Roundy and Madsen, 2016). The most common time-frame for rangeland seeding in the Great Basin is in the fall before soil freezing interferes with site preparation and seeding equipment (Plummer et al., 1968; Monsen and Stevens, 2004; Eiswerth and Shonkwiler, 2006). Germination in the fall, however, may make seeds vulnerable to preemergent seedling mortality (Boyd and Lemos, 2013; Hardegree et al., 2016). Hardegree et al. (2016) conducted sensitivity analysis on the effect of planting date on hydrothermal-germination response of several Great Basin native perennial grass species and cheatgrass (*Bromus tectorum* L.) and concluded that planting later in the fall can result in delayed germination and subsequent avoidance of postgermination winter mortality. Relating seedling establishment processes to climatic and weather conditions may suggest other ways that manipulation of germination timing could enhance seedling survival in this environment. Germination can be stimulated by priming or delayed by additives such as abscisic acid in seed coatings (Hardegree and Van Vactor, 2000; Badrakh, 2016; Madsen et al., 2016). An understanding of seasonal soil water and temperature conditions in the seedbed is critical to developing this approach (Flerchinger and Hardegree, 2004; Hardegree et al., 2016). Thermal, wet-thermal, and hydrothermal germination models have been proposed as tools for predicting germination timing under a wide range of potential environmental conditions in the field (Roundy et al., 2007; Rawlins et al., 2012; Hardegree et al., 2013).

The rangeland planting literature may be somewhat biased in that published studies primarily report field data from successful establishment outcomes that occur in years with average or above-average precipitation (Hardegree et al., 2011; Dwan et al., 2013). Most rangeland seeding studies are also limited to examining relatively short-term treatment effects, at relatively small spatial scales, and with a relatively low degree of temporal replication (Casler, 1999; Hardegree et al., 2011; Pyke et al., 2013). Full planning objectives are seldom met, and most field studies can claim only partial treatment success (Hardegree et al., 2011). Recent meta-analyses have assessed revegetation success parameters over much longer time periods and over large spatial scales (Eiswerth and Shonkwiler, 2006; Eiswerth et al., 2009; Gray and Muir, 2013; Sankey et al., 2013; Arkle et al., 2014; Knutson et al., 2014; Leger and Baughman, 2015; Monaco et al., 2017), but weather-related impacts in these studies typically only consider climatological averages and fail to incorporate seasonal or interannual variability. Rehabilitation and restoration goals are increasingly tied to ecological resistance and resilience, but our current understanding of these concepts also remains at the level of climatic averages without accounting for weather-mediated conditions or climate variability (Brooks and Chambers, 2011; Chambers et al., 2014a, 2014b, 2016; Miller et al., 2014).

Weather, Environmental Variability, and Successional/Adaptive Management

Dynamic successional processes that drive rangeland revegetation outcomes are nonlinear and can result in multiple potential trajectories (Westoby et al., 1989; Batabyal and Godfrey, 2002; Bestelmeyer et al., 2003). Our current understanding of rehabilitation and restoration management has also evolved to include specific strategies and tools to deal with the uncertainty inherent in these dynamic and variable systems, including the development of STMs (Briske et al., 2003, 2005; Bestelmeyer et al., 2009); adoption of successional planning and management paradigms (Roundy, 2005; Krueger-Mangold et al., 2006; Sheley et al., 2006; James et al., 2010; Davies et al., 2011); and adaptive management strategies (Herrick et al., 2006; Reever-Morghan et al., 2006; Briske et al., 2008; Williams, 2011). These tools and strategies acknowledge the potential impacts of weather but do not currently provide sufficient guidance on how to anticipate, quantify, or incorporate weather variability into management plans (Hardegree et al., 2012a, 2012b).

Successional rangeland rehabilitation and restoration models address the causes of succession and management treatments that directly or indirectly target underlying ecological processes (Sheley et al., 2006). These ecological processes are reflected in NRCS ESDs that are generally considered to be a key source of site information for rangeland revegetation planning (Bestelmeyer et al., 2003). ESDs provide local soil data but also information on the structure, composition, and dynamics of potential plant communities at a given field location (Caudle et al., 2013; NRCS, 2013). STM descriptions associated with ESDs provide managers with a conceptual map for management actions designed to move plant communities to a more desirable vegetation state (Briske et al., 2005). Historical weather information may be particularly relevant to transition probabilities associated with early establishment of desirable planted species after vegetation removal by wildfire (Hardegree et al., 2012a, 2012b). One useful planning supplement to ESDs may be a synopsis of historical climate information relevant to key life-cycle transitions in early plant establishment (Hardegree et al., 2013, 2016). Historical precipitation data can be used to assess both the long-term variability and the probability of favorable site conditions for both initial establishment and later successional processes (Hardegree et al., 2012b).

Successional rehabilitation and restoration strategies are based on management interventions designed to improve site availability, species availability, and species performance (Cox and Anderson, 2004; Roundy, 2005; Krueger-Mangold et al., 2006; Sheley et al., 2006; James et al., 2010). Year-to-year variability in weather, however, can have a dominant influence on treatment outcomes (Vaughn and Young, 2010; Hardegree et al., 2011). Successional establishment strategies mitigate this type of uncertainty through iterative/adaptive management (Reever-Morghan et al., 2006; Williams et al., 2009; Sheley et al., 2010; Williams, 2011; Leffler and Sheley, 2012). The literature suggests that positive treatment effects require favorable weather conditions but also generally result in only partial success relative to initial management goals (Hardegree et al., 2011). A long-term contingency-based adaptive-management strategy would require a framework for making supplementary decisions in the future that cannot be explicitly predicted at the beginning of a given planning cycle or event (Nie and Schultz, 2012). The need for contingency-based management planning has been acknowledged in recent US Department of Interior guidance on adaptive management (Williams et al., 2009) but has yet to be fully implemented under current ESR and National Environmental Policy Act (NEPA) planning guidelines (USDI BLM, 2007, 2008). A contingency-based adaptive-management planning framework (Fig. 2) would need to acknowledge the uncertainty associated with individual management actions and have a system in place for supplemental decision making under future, and unknown, conditions of plant community composition and function, with a general goal of maintaining a positive trajectory toward a more desirable plant community (Roundy, 2005; Krueger-Mangold et al., 2006; Sheley et al., 2006; James et al., 2010).

A second element of adaptive management is to develop new knowledge simultaneously with the implementation of management treatments (Reever-Morghan et al., 2006). The traditional approach for “learning while doing” involves testing out multiple treatment options, evaluating their success, and selecting the more successful ones for future management (Allen et al., 2011). Unfortunately, single-year management actions are not replicated for general inferences that would apply to other sites and years without a relatively sophisticated experimental design (Vaughn and Young, 2010; Hardegree et al., 2011). A more weather-centric approach would require interpretation of individual-year results through the lens of weather conditions during an individual field trial (Fig. 3; Monaco et al., 2016). Development of predictive models for rangeland-revegetation success from these data may require additional meta-analyses across multiple field conditions in which relative weather for a given site and year are covariables (Michener, 1997; Johnson, 2006).

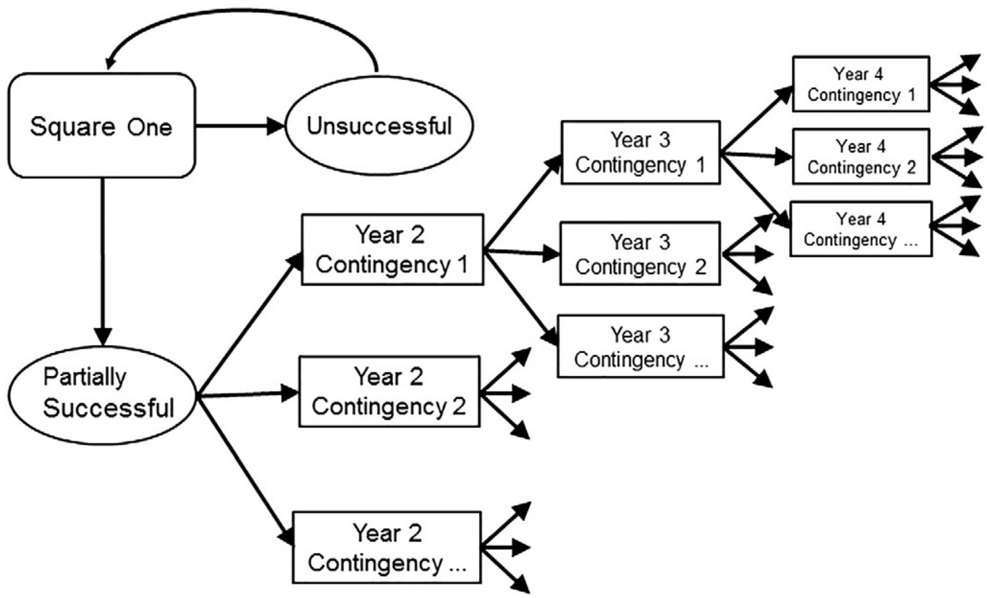

Figure 2. A weather-centric, contingency-based adaptive management plan would require a framework for making multiyear decisions under high levels of uncertainty for the impacts of individual management decisions. This would probably require a decision-making framework rather than an explicit plan for implementation of future management treatments.

Weather Information and Tools

Weather-centric rangeland restoration planning requires a broad spectrum of information for effective management across multiple spatial and temporal scales (Fig. 4). In-situ meteorological observations across the Intermountain West are geographically sparse and subject to gaps in data records (Hardegree et al., 2012a). Landscape heterogeneity associated with varied topography also makes it challenging to interpolate data from existing meteorological stations to infer weather variables at unmonitored field sites (Thornton et al., 1997; Abatzoglou, 2013). Accurate estimates of spatial and temporal weather parameters are essential for retrospective assessment of historical planting treatments and for establishing a probabilistic expectation for future adaptive management treatments.

Seasonal climate forecasts could greatly enhance the cost effectiveness of revegetation and restoration decisions given the low probability of favorable conditions in any given year. Incorporation of seasonal forecast technology into the decision schematic in Figure 2 would allow for the option of deferring restoration or rehabilitation activities in years without a strong signal of favorable climate conditions for establishment. Alternatively, a robust forecast for favorable climatic conditions could be used to trigger contingency plans in areas that have been previously identified for rehabilitation or restoration and for which premanagement logistics of equipment, personnel, and

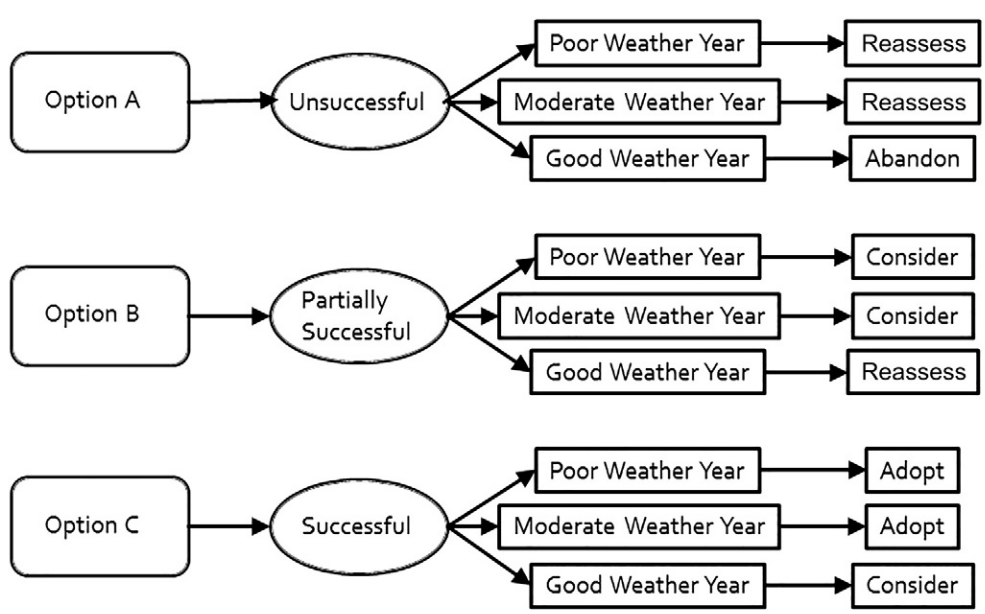

Figure 3. Weather informed learning through adaptive management. Individual treatments in single years do not provide sufficient degrees of freedom for broad inferences and equivocal results from years with extremely good or extremely bad weather probably need to be reassessed. Interpretation of management actions could, however, be derived from meta-analysis in which individual year effects were weighted by weather conditions during the treatment.

Full-Spectrum Weather Information for Science and Management

Historical Observations

- Gridded data for sites with no meteorological instrumentation.
- Retrospective analysis of historical treatments.
- Calibration and validation of environmental models
- Sensitivity analysis of weather effects.

Seasonal Forecasts

- Real-time use by land managers for decision making.
- Cost-effective decisions for weed management, species selection and planting decisions.
- Skill assessment and probabilistic planning.

Climate Change Projections

- Downscaled and disaggregated weather-data format for model simulations.
- Mitigation and adaptive management strategies for alternative future climate scenarios.

Figure 4. Broad-spectrum tools for rangeland restoration decision-making across multiple spatial and temporal scales.

plant materials are in place (Westoby et al., 1989; Bakker et al., 2003; Hardegree et al., 2012a, 2012b, 2013).

Longer-term climate projections are key to the development of mitigation and adaptive management strategies for many state and federal land management agencies (GAO, 2013). Climate projections have previously been used in conjunction with species-distribution/habitat-suitability models to predict potential future trajectories of both weed invasion risk and restoration opportunities (Bradley and Wilcove, 2009; Bradley, 2010, 2014). Downscaled and disaggregated weather scenarios derived from GCM output would also facilitate the use of more mechanistic models to assess potential climate change effects on habitat suitability (Hardegree et al., 2013).

Historical Observations

Advances in regional monitoring have been made over the past few decades with the advent of various meteorological networks specifically deployed for snow monitoring (SNOTEL: http://www.wcc.nrcs.usda.gov/snow/), wildland fire applications (RAWS network: http://raws.fam.nwcg.gov/), and region-specific agricultural applications (AgriMet: http://www.usbr.gov/pn/agrimet/); however, high-quality long-term (30+ yr) in-situ observations remain relatively sparse over most of the western United States and are primarily located along transportation corridors and in areas of noncomplex terrain.

Various methods to estimate weather and climate data across space have been developed to enhance interpolation of station observations by incorporation of physiographic information such as elevation and aspect. Examples include the Parameterized Regression on Independent Slopes Model (PRISM, available at 800-m and 4-km resolution; Daly et al., 2008), DayMET (~1-km resolution; Thornton et al., 1997), and TopoWX (~1-km resolution; Oyler et al., 2014).

Abatzoglou (2013) developed a gridded daily surface meteorological dataset for the conterminous United States from 1979 to the present at a spatial resolution of 2.5 arc minutes (~4 km) that blends the temporal attributes and variables from the North American Regional Reanalysis (Mesinger et al., 2006) and the National Aeronautics and Space Administration's North American Land Data Assimilation System (NLDAS-2; Mitchell et al., 2004) with the higher spatial resolution data attributes from PRISM. This dataset (gridMet, http://metdata.northwestknowledge.net) provides daily output of precipitation (Fig. 5), minimum/maximum temperature, minimum/maximum relative humidity, specific humidity, dew point, surface downward shortwave radiation and wind velocity, as well as derived estimates of reference potential evapotranspiration and fire danger indices. An independent validation of the gridMET dataset shows that it has demonstrated skill at capturing daily weather observations from a variety of stations located across the Intermountain West (Abatzoglou, 2013; McEvoy et al., 2014).

Seasonal Climate Forecasts

Skillful forecasts from numerical weather models are currently limited to a short-term time horizon of 7 – 10 days. Weather forecasts rely on initial conditions to create a deterministic prediction of future conditions by solving a set of numerical equations that govern atmospheric motion. Seasonal climate forecasts use the same set of equations but rely more on the slowly evolving components of the climate system, such as ocean temperatures, concentration and extent of sea ice, and soil moisture, and how they influence atmospheric thermodynamics and circulation patterns. These seasonal climate forecasts can provide skillful information (e.g., monthly and seasonal temperature and precipitation) over longer time periods of several months but are not intended to provide forecasts for specific days like the more commonly used weather forecast models (Doblas-Reyes et al., 2013). The North American Multi-Model Ensemble (NMME, Kirtman et al., 2014) consists of seasonal climate forecasts from several different climate models for lead periods of up to 9 mo.

The availability of seasonal climate forecasts and their utility in decision making is impaired by the spatial scale of available data, accessibility of forecast data, lack of knowledge of the forecast accuracy for many applications, and difficulty in transforming forecast data into metrics that are meaningful for applied use. To overcome the mismatch in spatial resolution of native NMME forecasts (~200 km) and the resolution needed for location-based modeling and management applications, Barbero et al. (2017) statistically downscaled monthly NMME forecasts to a 4-km resolution for the western United States (west of 103°W) using the historical gridMet data of Abatzoglou (2013). This statistical downscaling method used the bias correction and spatial disaggregation method of Wood et al. (2002) and Wood and Lettenmaier (2006) and temporally disaggregated daily minimum/maximum temperature, downward solar radiation, wind speed, specific humidity, precipitation, and dew-point temperature. Downscaled seasonal climate forecasts from several climate modeling groups for the subsequent 7 mo (http://climate.nkn.uidaho.edu/downscaledForecast/) are currently available and are being updated automatically near the middle of each month.

The skill of seasonal downscaled forecasts can be assessed by pairing hindcasts (forecasts initialized and made for historical data) with observations. Barbero et al. (2017) found significant skill (e.g., forecasts better than using climatological averages) over 1982 – 2010 for seasonal temperature and precipitation across the western United States, with generally higher skill for temperature than precipitation, and significant geographic and seasonal variability (Fig. 6). Although forecast skill for

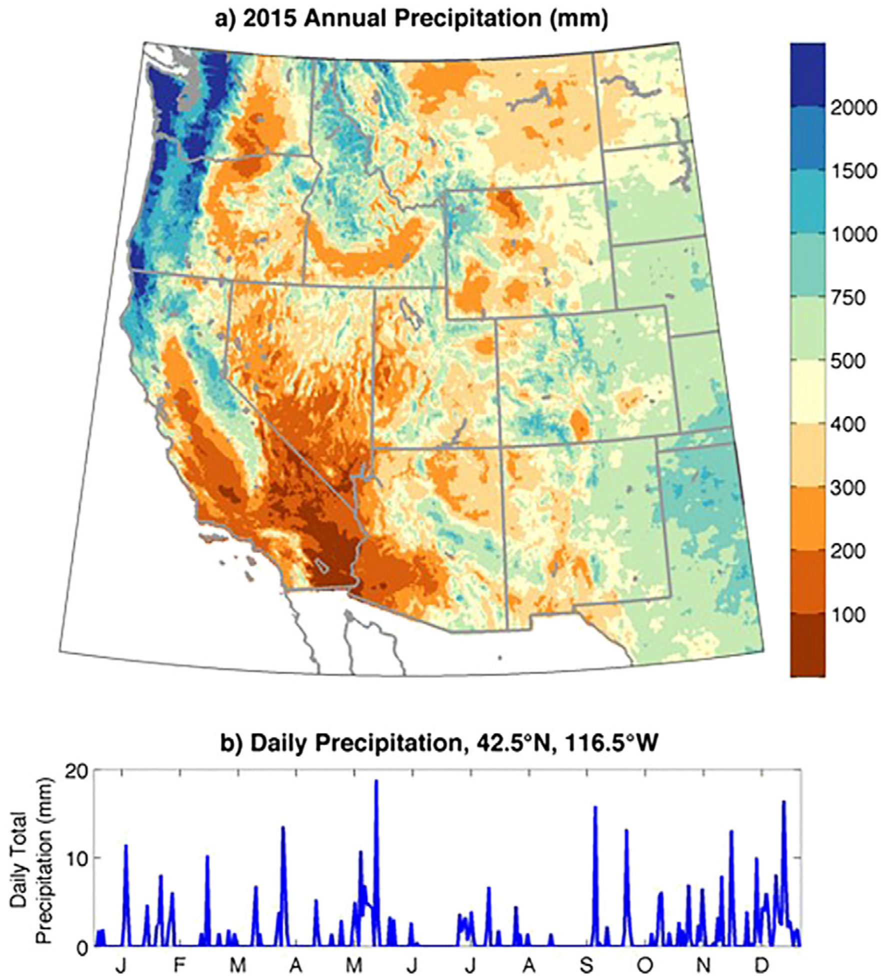

Figure 5. Annual calendar-year precipitation totals for 2015 from the gridMET database and a daily time series of precipitation for a site in southwestern Idaho.

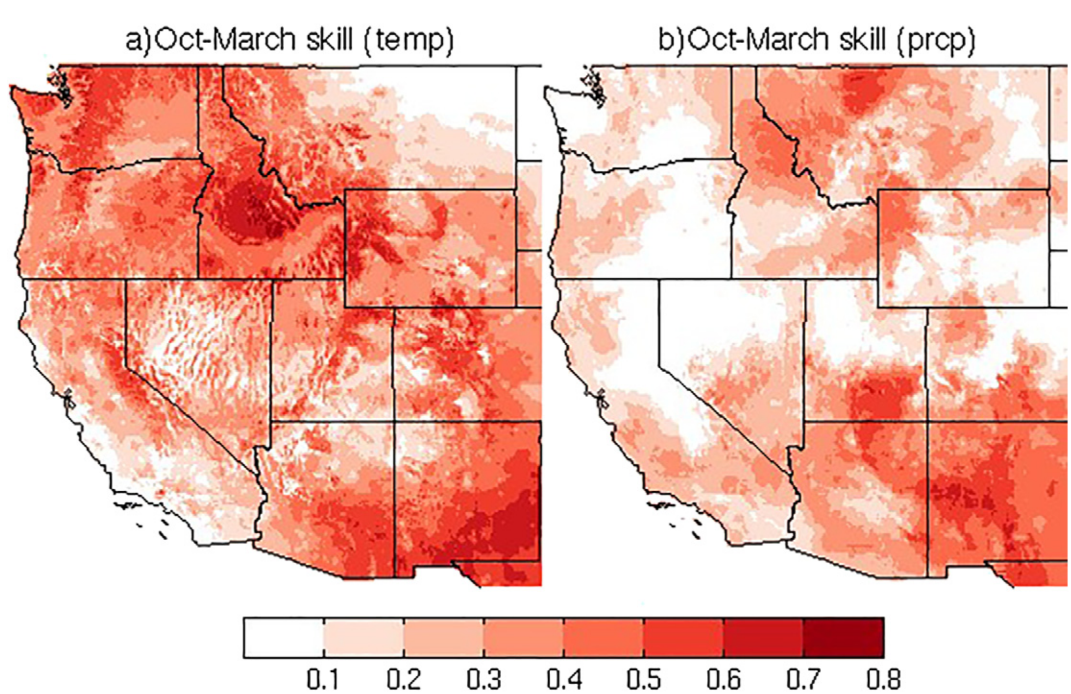

Figure 6. Pearson's correlation coefficient of North American Multi-Model Ensemble mean seasonal forecasts made in October for October—March (**a**) temperature and (**b**) precipitation with observations from gridMET for 1982—2010.

individual months decreased with lead time, statistically significant skill was found over approximately half of the western United States for aggregated 3- to 6-mo forecasts (Barbero et al., 2017).

Given the episodic nature of favorable establishment conditions in the Great Basin, management recommendations based on seasonal forecasts may be limited to only those years with relatively large signals for favorable conditions in the winter and spring. Further research is warranted to estimate forecast skill associated with the specific, and relatively infrequent climate patterns associated with establishment success.

Downscaled Climate Change Projections

Climate projections use a similar suite of models as the NMME seasonal forecasts but applied over a much longer time horizon. Climate projections, however, also consider long-term changes in concentrations of greenhouse gases and aerosols, as well as solar variability. Climate projections are not intended to provide forecasts for specific days or years, but rather information about climate (e.g., normals, variability, extremes) for future multidecadal time periods. The fifth phase of the Climate Model Intercomparison Project (CMIP5) (Taylor et al., 2012) provides climate outputs from multiple global climate models (GCM) for a set of anthropogenic scenarios (e.g., greenhouse gas emissions) over the next century.

Similar to raw output from seasonal climate forecasts, CMIP5 model output is produced at a lower spatial resolution than is needed for most modeling studies and applications. To remedy this, GCM output is typically downscaled using empirical methods or dynamical models. For example, the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown, 2012) has been used to statistically downscale 20 GCMs over the conterminous United States using both historical (1950 − 2005) and future (2006 − 2099) climate experiments. This dataset (available at http://maca.northwestknowledge.net) provides daily output scenarios for precipitation, minimum/maximum temperature, minimum/maximum relative humidity, specific humidity, surface downward shortwave radiation, and 10-m wind velocity. As these data are also downscaled to 4-km using the gridMET dataset, they are compatible with historical gridMET observations and seasonal climate forecasts.

The size and complexity of these historical and forecasting datasets often limits their utility to stakeholders that may only require information for a specific site or application. We have created a number of web services to disseminate historical data, seasonal climate forecasts, and future climate projections in a variety of formats (http://climate.nkn.uidaho.edu/downscaledForecast/downloadModels.php). Users can download data for specific geographic locations in a simple text format or spatial-gridded data in NetCDF format. Users also have the ability to visualize forecast data and forecast skill as time series for either a point location or relative to a map of the western United States. Users can also visualize skill tables for the forecast data at different lead times and outlooks over the different models and variables.

The Path Forward: Use of Weather Knowledge to Improve Management

A stated objective of most postfire treatments is to stabilize soils, specifically by mitigating impacts of potential erosion in the absence of plant cover. Erosion is a fundamental mechanism of soil degradation after wildfire and results from primary weather impacts of wind and precipitation. Wind events exceeding 6 − 9 m/s can lead to loss of the thin topsoil, which contains the most fertile soil components and both planted and naturally deposited seed (Hasselquist et al., 2011). Soil stability from returning plant cover may take 3 − 11 or more months following summer wildfire (Sankey et al., 2009a). Predicting the timing and location of potential erosion risk could help guide seeding and planting investments and prevent exacerbation of erosion by postfire management actions (Miller et al., 2012). Erosion risk assessment models are currently available for water erosion (Al-Hamdan et al., 2015) but less information is available on the risk of wind erosion in western rangeland environments. The few available data sets suggest that while wind erodibility may have predictable relationships to variation in humidity over time, rain events can either increase or decrease erosion (Sankey et al., 2009b). Assessment of weather effects on wind erosion is particularly problematic at spatial and temporal scales appropriate for large fire-rehabilitation projects, but routine erosion monitoring and correlation with weather data would be an important step forward in the interpretation of ESR project success.

Current ESR planning procedures and time frames may be too limiting to incorporate weather information and adaptive-management concepts (Hardegree et al., 2012a). Although ESR objectives emphasize site stabilization, this program provides a large investment in what is essentially a first step in effective restoration of degraded rangeland systems. There are tremendous opportunities to leverage these resources by following up with longer-term planning strategies under NEPA guidelines. NEPA-compliant rehabilitation and restoration plans, however, suffer from a similar short-term perspective on revegetation practices, do not currently recognize the large potential impacts of weather and climate variability, and do not adequately provide for adaptive management needs in an uncertain future (Williams et al., 2009; Nie and Schultz, 2012). New guidelines would need to be developed to allow for NEPA compliance in revegetation plans that could also accommodate contingency-based decision making under unknown future weather conditions.

Private-land revegetation planning is inherently more flexible, and many revegetation and restoration-related activities are supported with NRCS conservation management program assistance (Briske, 2011). Rangeland seeding guidelines under current NRCS conservation practice standards, however, do not include guidance for adaptive management or consideration of weather impacts on potential revegetation success (Hardegree et al., 2011). Rangeland conservation practice standards could easily be updated, however, to include consideration of successional processes and STM concepts given that NRCS is the principal producer of ESD and associated STM information (Herrick et al., 2006; Caudle et al., 2013; NRCS, 2013).

Barriers to Use of New Technology

Site-specific weather information can lead to better management decisions, but ecological issues are only part of the calculus that a manager must consider when planning a rehabilitation or restoration project. Also important are a number of contextual questions about budget, seed availability, and affordability, likely interest-group response to proposed field methods, and pressures from political entities or local residents. Uptake of weather-centric technology will also depend on the ability of the revegetation infrastructure to adopt new technology and innovation (Pannell et al., 2006; Rogers, 2010). Innovation adoption depends on the characteristics of the manager who is considering a change in practice; characteristics of the innovation under consideration; and the prospective innovator's social system (Didier and Brunson, 2004). For most western US rangelands, the relevant social systems are local community members, including grazing permittees; the agency that employs the manager; other federal agencies whose regulations affect the implementation of rangeland management; and state and federal legislators that may seek to influence management decisions. These elements can either facilitate or constrain adoption. We identify four categories of constraints that can serve as barriers to uptake of a new technology:

- Ecological—e.g., weather and climate, previous disturbance and use history, specific features of the site or landscape
- Economic—costs of implementation, access to budgets
- Social/political—e.g., perceived local impacts of revegetation or disturbance, pressure to reintroduce livestock after a wildfire, trust levels among local communities or advocacy groups, higher-level political pressure

- Institutional—e.g., adequacy of staffing, local office customs, legacy of prior bad outcomes, local or agency-wide policies that limit flexibility

Any of these barriers can interfere with the use of new or innovative science solutions. Scientists often assume that dissemination of new knowledge is sufficient to stimulate a change in behavior of managers and practitioners (Miller, 1998; Cortassa, 2016). Hunter (2016) found, through surveys and interviews, that although the utility of research was acknowledged to be most useful in the planning stage of field treatments, many fire and fuel specialists were unaware of specific science applications for wildfire management and response (e.g., fuels management, postfire rehabilitation, smoke management). Interviewees frequently cited this lack of manager awareness as a barrier to the use of science but also reported lack of resources or time, uncertainty about whether the science was settled, and political barriers both within and outside the management organization. Another survey asked 500 fire and fuels specialists to agree or disagree about 16 potential barriers to using research. Less than half agreed that factors related to knowledge were significant, but more agreed that pressure from political figures, interest groups, and the general public; conflicting agency policies and directives; lack of rewards for using research; and limited discretion in decision making were significant barriers to the use of new science (Wright, 2010). The most agreed-upon barrier, however, by 70% of respondents, was “lack of time” for incorporating new science into management. Land managers must be able to seek out new science when it is needed, perhaps learn new techniques, train colleagues and subordinates how to use the new tool or technique, obtain site-level data necessary to use the tool/technique (which might not be readily available), and monitor effects of first-time implementation to determine whether it has led to an improved outcome. When Whitcomb (2016) interviewed and surveyed federal rangeland managers in the Great Basin and Mojave Desert regions about their likelihood of using new scientific findings from studies of plant responses to climate and wildfire (Lybbert and St. Clair, 2016; St. Clair et al., 2016), respondents cited time and financial or staffing resources as significant barriers. Whitcomb (2016) also compared public opinions about postwildfire rehabilitation with managers’ beliefs about public opinion and found that land managers consistently predicted greater disagreement than was supported by the survey. Both the land manager community and the public supported the following statement: “project choices should be based on proven scientific research” (61% and 58%, respectively).

Two authors of the current publication (Meredith and Brunson) explored this question, in the specific context of weather-centric rehabilitation and restoration planning, through a series of qualitative, semistructured interviews of individuals ($N = 11$) involved in either restoration or postfire rehabilitation planning. Most interviewees reported consulting existing online weather-oriented resources such as USDA-NRCS SNOTEL data and datasets from the PRISM climate group (http://www.prism.oregonstate.edu/), as well as land- and vegetation-oriented products, such as USDA-NRCS soil and ESD information, and imagery from the National Aerial Photography Program. Online sources were also used to inform choices of seed mixes and to learn about prior revegetation successes and failures. Online weather, soil, and remote sensing data, however, were not always viewed as useful and reliable and interviewees tended to view these as secondary resources that were not weighed as heavily as personal or local office experience. Interviewees expressed particular distrust of computer models, which tended to be viewed as speculative at best. Time constraints, a lack of ground-truthing, external social/political pressures, and complexity are all viewed as potential barriers to use of weather-centric online decision-support tools.

Science/Manager Partnerships for Effective Implementation

Given the apparent reluctance of land managers to embrace new scientific tools for decision making, what options are open to scientists hoping to improve adoption of new weather-centric revegetation decision-support tools? Agency directives could certainly increase adoption, but such top-down mandates invariably meet resistance among those charged with implementing them and implementation is usually not standardized (Sabatier, 1986; Long and Franklin, 2004). In the medical field, where such top-down directives are more common, both mandates and technical assistance have been shown to be less effective at stimulating adoption than financial incentives (Chor et al., 2015). Collaboration, however, among policy makers, researchers, and likely implementers appears to be the most effective (Finnerty et al., 2014). The adoption of new revegetation planning tools, therefore, is likely best facilitated through the work of boundary-spanning organizations that link science to practice.

One such boundary-spanning organization is the Fire Science Exchange network established by the federal Joint Fire Science Program. Organizations such as the Great Basin Fire Science Exchange and Southwest Fire Science Consortium have brought together scientists and land managers who collaborate to provide implementation guidelines for wildfire, rehabilitation, and restoration science via accessible products such as webinars, nontechnical summaries, research syntheses, and links to online tools. These collaborations are intended to break down the “firewall” between academic research and on-the-ground practice. Because poor tool design can become a barrier to adoption, scientists should partner with web-interface specialists, game designers, and data-visualization experts in developing new online resources. Ultimately, science is most usable when the prospective users themselves are engaged at multiple stages in the research and development process (Tanaka et al., 2016). Examples of direct user-researcher engagement in scientific inquiry include large-scale experiments such as the Sagebrush Steppe Treatment Evaluation Project (SageSTEP; McIver and Brunson, 2014; McIver et al., 2014), as well as smaller-scale producer-researcher partnerships supported by the USDA’s Western Sustainable Agriculture Research and Education program (Rasmussen et al., 2013). Studies such as these could be designed to test assumptions underlying weather-centric restoration tools, assess strategies to adapt restoration efforts to current climate conditions, and retrospectively evaluate the link between weather patterns and post-treatment plant community response.

Conclusions and Management Implications

Integration of ESR and NEPA planning in support of long-term vegetation management objectives would require significant changes to the logistical and policy framework supporting revegetation activities on federal rangelands. While reactive post-wildfire rehabilitation will continue to be critically important, long-term improvement in rangeland conditions may require greater use of proactive, NEPA-compliant restoration plans that allow managers to take advantage of favorable weather conditions. Such a shift in priorities would likely require greater capacity in terms of budget and personnel, as well as authority to postpone plans if seasonal climate forecasts predict suboptimal conditions for planting in a particular season. It may also require a shift in agency culture to encourage innovation by field-level managers, as well as ongoing activities to engage local communities and regional stakeholders in the processes that lead to revegetation choices. Boundary-spanning organizations can be enlisted to facilitate multistakeholder collaborations and help train managers in the application and limitations of new decision-making tools.

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