Part 2

Principles and Practices to Influence Ecosystem Change

6 Weather Variability, Ecological Processes, and Optimization of Soil Micro-environment for Rangeland Restoration

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Introduction

Precipitation, solar radiation, wind speed, air temperature, and humidity are principal drivers controlling energy and water flux in plant communities. Climate is defined as the long-term average representation of these variables, and their seasonal pattern. Rangelands are generally characterized by an arid or semi-arid climate with plant communities dominated by grassland, shrub-steppe, and savanna vegetation. Gross climatic variability generally determines the suitability of both native and introduced plant materials for rangeland restoration and rehabilitation (Shown *et al*., 1969; Shiflet, 1994; Barbour and Billings, 2000; Vogel *et al*., 2005; USDA, 2006). Unfortunately, the micro-environmental requirements for germination, emergence, and seedling establishment are much more restrictive than the longer term climatic requirements for maintenance of mature plant communities (Call and Roundy, 1991; Peters, 2000; Hardegree *et al*., 2003).

Weather is also the combined expression of climatic variables, but over a relatively short time scale. Rangelands are relatively dry in a climatological sense, but exhibit high spatial and temporal variability in weather (Rajagopalan and Lall, 1998). Figure 6.1 demonstrates annual and seasonal variability in precipitation for a rangeland site in southern Idaho, USA that receives 295 mm of average annual precipitation. Weather is even more variable at the level of seasonal distribution (Fig. 6.1; Table 6.1), which is the relevant scale for critical phases of germination, emergence, and seedling establishment.

Individual plants respond to their local micro-environment in which weather inputs are moderated by interactions with other plants, the soil surface, and lower soil layers (Campbell and Norman, 1998). Soil development is itself affected by weather and climate, but also by the resident vegetation, underlying parent material, topography, soil age, and other factors, all of which are highly variable over space (Jenny, 1980). The soil micro-environment is most variable in near-surface layers that respond quickly to changes in atmospheric variables (Flerchinger and Hardegree, 2004). Deeper soil layers can store precipitation and buffer establishing plants from unfavorable weather conditions, but the majority of mortality events among seeded species occur relatively near the soil surface at, or before, the relatively vulnerable stage of seedling emergence (James *et al*., 2011). Existing plant cover shades the soil surface and provides protection from wind-driven evaporation, but competition for moisture from invasive weeds can be a dominant limiting factor for water availability in the seedbed. Seedbed preparation and planting

 Invasive Plant Ecology and Management: Linking Processes to Practice (eds T.A. Monaco and R.L. Sheley)

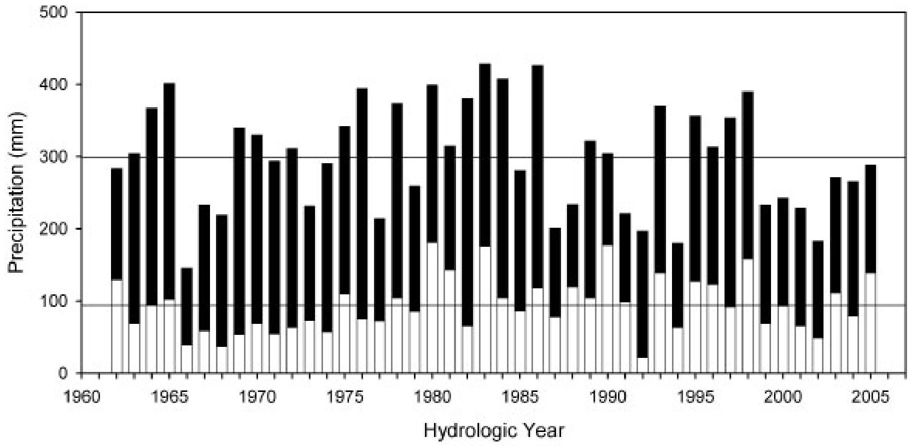

Fig. 6.1. Annual (black bars) and March–May precipitation (white bars) for Boise, Idaho, USA. Mean annual precipitation and standard error of the mean (SE) for this location is 295 ± 11 mm but the standard deviation of the mean (SD) is 68 mm with a coefficient of variation (CV) of 24%. March–May precipitation is relatively more variable with a mean and SE of 93 ± 6 mm, an SD of 38 mm, and CV of 41%.

Table 6.1. Mean monthly precipitation (mm) for rangelands with similar annual precipitation. Numbers in parentheses represent the standard deviation of the mean.

	Boise (USA)	Urumqi (China)	Windhoek (Namibia)	Neuquen (Argentina)	Ivanhoe (Australia)
January	35 (20)	8 (6)	64 (60)	13 (20)	33 (43)
February	27 (17)	9 (7)	77 (61)	17 (25)	30 (42)
March	31 (18)	19 (13)	70 (65)	26 (36)	29 (36)
April	29 (18)	31 (20)	24 (22)	22 (29)	20 (28)
May	33 (26)	33 (23)	4 (7)	19 (18)	29 (25)
June	22 (18)	33 (23)	2 (7)	26 (26)	23 (19)
July	7 (8)	28 (21)	1 (2)	18 (19)	24 (20)
August	7 (12)	21 (21)	0 (1)	15 (17)	24 (20)
September	14 (16)	24 (17)	2 (3)	19 (23)	23 (19)
October	20 (15)	21 (14)	10 (18)	28 (25)	31 (31)
November	34 (16)	18 (10)	18 (21)	19 (22)	24 (23)
December	36 (22)	13 (8)	27 (27)	19 (29)	24 (27)
Annual	295 (68)	258 (74)	299 (141)	241 (144)	314 (131)

methods are designed to optimize micro-environmental conditions for planted species, to increase the number of favorable microsites for germination and establishment, and to mitigate or control competition for water and other resources from undesirable species (Roundy and Call, 1988; Call and Roundy, 1991; Sheley *et al*., 1996, 2006; Krueger-Mangold *et al*., 2006).

Published research on rangeland restoration seldom addresses the issue of weather variability *per se*. Hardegree *et al*. (2011) surveyed the rangeland planting literature for the western USA and observed that less than 60% of studies reported weather conditions, and less than half were replicated for year effects that would have included weather as a variable factor. In studies that did report weather conditions, successful establishment was almost always associated with what would be considered average or above average precipitation during the study period. This implies that climatic thresholds exist, below which, management actions have little effect on establishment success. In practice, most rangeland restoration activities make limited use of weather and climate information. Climate and gross soil differences are generally considered only in the selection of appropriate plant materials based on the potential distribution of mature-plant communities. Seedbed preparation and planting techniques are designed to optimize seedbed micro-environment but these methodologies are used prescriptively regardless of historical or potential weather conditions. Weather information is mostly used retrospectively to explain seeding failure.

Rangeland restoration practices are generally viewed in the context of a successional model that recognizes the causes of succession and ecological processes that are amenable to management (Pickett *et al*., 1987; Westoby *et al*., 1989; Whisenant, 1999; Bestelmeyer *et al*., 2003; Roundy, 2005; Krueger-Mangold *et al*., 2006; Sheley *et al*., 2006). Sheley *et al*. (2010) and James *et al*. (2010) outline these processes, and the ecological principles that define management alternatives for invasive plant management and rangeland restoration. All of the ecological processes underlying succession are directly or indirectly affected by weather and climate. Sheley *et al*. (2010) also describe a generalized planning cycle that includes initial site assessment, monitoring, adaptive management, and reassessment of management effects. Site assessment and adaptive management are two steps in the planning cycle that can be significantly improved by incorporation of weather and climate information. In the following sections, we use the ecologically based model described by Sheley *et al*. (2010) to structure a discussion of weather and climate impacts on some key processes affecting succession, the micro-environmental underpinnings of some important restoration management tools, and strategies to incorporate weather information into the restoration-planning cycle.

Weather, Climate, and Successional Processes

Site availability and optimization of seedbed micro-environment

Disturbance is the principal ecological process affecting site availability for rangeland plant establishment (Sheley *et al*., 2010). Soil disturbance can favor invasive over desirable species, but some type of mechanical disturbance is generally necessary to create safe sites for establishment of desirable, late-successional species (James *et al*., 2010). Seedbed preparation and planting methods are designed to reduce water loss and mitigate adverse thermal conditions in the seed zone. This is generally accomplished through mechanical disturbance, soil firming and surface modification, control of seeding depth, and less frequently, the application of soil surface amendments (Roundy and Call, 1988; Sheley *et al*., 1996).

Soil surface modification is often used to increase water availability to the seed. Alternative seedbed preparation strategies can alter seedbed micro-environment by improving seed–soil contact, reducing the amount of surface area subject to evaporation, improving infiltration and water holding capacity, and creating microsites that capture and retain water (McGinnies, 1959; Roundy *et al*., 1992). Animal trampling, land imprinting, pitting, furrowing, and rolling treatments have all been used to create microsites that capture or preserve moisture, and to improve hydraulic conductivity by pressing surface-applied seeds into the soil (Hyder and Sneva, 1956; McGinnies, 1962; Haferkamp *et al*., 1987; Winkel and Roundy, 1991; Roundy *et al*., 1992). Post-disturbance soil firming can improve hydraulic conductivity to drilled seeds by reducing soil surface area and soil macroporosity (Hyder and Sneva, 1956; McGinnies, 1962). Various studies have also reported differential establishment success relative to the position of soil surface features that affect local micro-environment (Bragg and Stephens, 1979; Eckert *et al*., 1986; Roundy *et al*., 1992). Surface modification, however, can also cause seed burial beyond establishment depth (Kincaid and Williams, 1966; Slayback and Renney, 1972; Winkel *et al*., 1991a).

Mulch application can reduce water loss and moderate soil surface temperatures but is generally considered too expensive for extensive rangeland use (Lavin *et al*., 1981; McGinnies, 1987; Ethridge *et al*., 1997). Hardegree *et al*. (2011) found that mulch application improved seedling establishment in only 62% of 21 rangeland seeding studies surveyed. Mulch application has a more consistent record, however, for erosion control and soil stabilization, which can have positive secondary effects on soil microsite availability (Bautista *et al*., 1996; Brockway *et al*., 2002; Benik *et al*., 2003).

Depth of planting is a critical factor in successful plant establishment as microsite favorability is depth dependent (Young *et al*., 1990; Winkel and Roundy, 1991, Chambers and MacMahon, 1994; Ott *et al*., 2003). The physical rationale for depth recommendations is based on a tradeoff between increased water availability and increased energy requirements for emergence as a function of depth (Roundy and Call, 1988; Call and Roundy, 1991). Evidence for depth effects is generally limited to relatively small but detailed studies conducted in the laboratory, and less frequently, in the field (Kinsinger, 1962; Vogel, 1963; Hull, 1964). There are many rangeland seeding studies that compare establishment success of broadcast and planted seeds (e.g. Nelson *et al*., 1970; Wood *et al*., 1982; Haferkamp *et al*., 1987; Ott *et al*., 2003), but very few have actually characterized post-planting seed depth (Winkel and Roundy, 1991; Winkel *et al*., 1991a, b). These studies generally support the hypothesis that very small seeds establish more frequently from near-surface seed placement, larger seeds require soil cover for maximal performance, and seed performance drops dramatically below some threshold of depth (Hull, 1948; Stewart, 1950; Douglas *et al*., 1960). Seeding depth recommendations can be fairly specific, but are based on rules of thumb regarding seeding depth as a function of seed size (Plummer *et al*., 1968; Jensen *et al*., 2001; Monsen and Stevens, 2004; Lambert, 2005; Ogle *et al*., 2008a, b). The decision to broadcast or plant seeds, however, is often mandated by topographic complexity and economic considerations.

Seeding rate and optimization of species availability

Rangeland restoration is often conducted in areas that have lost their source of native plant materials, and availability of desirable species can only be addressed by seeding. Seeding rate recommendations are linked to microclimatic considerations as increased seed numbers increase the probability of seeds reaching safe microsites, irrespective of active depth management (Harper *et al*., 1965; Roundy *et al*., 1992; Chambers, 1995). Most individual studies reporting effects of seeding rate on establishment success are not replicated sufficiently to evaluate interactions with annual and seasonal variability in weather conditions. The combined literature, however, supports the concept that higher seeding rates may enhance the likelihood of successful initial establishment (Vogel, 1987; Sheley *et al*., 1999; Wiedemann and Cross, 2000; Williams *et al*., 2002; Eisworth and Shonkwiler, 2006; Hardegree *et al*., 2011). Broadcast seeding rates are generally recommended at 2–3 times the rates for planted seeds to increase the likelihood that sufficient seeds find safe sites for establishment (e.g. Nelson *et al*., 1970; Wood *et al*., 1982; Haferkamp *et al*., 1987; Ott *et al*., 2003).

Species performance and competition for resources

Climate is the primary criterion for selection of acceptable plant materials for rangeland restoration. This is generally acknowledged in most seeding guides in the form of tables that list species and cultivar suitability as a function of mean annual precipitation (e.g. Jensen *et al*., 2001; Lambert, 2005; Ogle *et al*., 2008b). Seeding guides may also cite climatic thresholds below which active seeding practices are not recommended due to the low probability of success (Anderson *et al*., 1957; Jordan, 1981). Vegetation distribution as a function of climate is the basis of most recommendations for native plant materials (e.g. Barbour and Billings, 2000; USDA, 2006), but cultivar-specific recommendations can also be based on plant materials evaluation and development by local and regional government, and academic organizations (Schwendiman, 1956; Harlan, 1960; Alderson and Sharp, 1994; Asay *et al*., 2003). Plant materials are often selected or bred for superior establishment, growth, and production within a targeted region or climatic regime (Schwendiman, 1958; Johnson and Asay, 1995; Asay *et al*., 2003). Current plant materials development and evaluation programs are increasingly focused on parameters related to species performance and establishment under alternative conditions of weather and climate (Aguirre and Johnson, 1991; Johnson and Asay, 1995; Arredondo *et al*., 1998; Jensen *et al*., 2005).

Asay *et al*. (2001) have argued that the relatively harsh climatic conditions on rangelands may preclude the effective use of many native plant materials, and that it may be prudent to plant more easily established non-native species. Indeed, biodiversity and restoration objectives may require multiple-year strategies for replacement of non-native species only after initial site stabilization and suppression of annual weed competition (Bakker *et al*., 2003; Cox and Anderson, 2004). Biodiversity and restoration objectives may need to be addressed only in years when climatic conditions are amenable (Holmgren and Scheffer, 2001; Hardegree *et al*., 2003; Cox and Anderson, 2004; Hardegree and Van Vactor, 2004).

Species performance can be optimized by selecting the most appropriate season for planting. Optimal planting season is determined by the historical pattern of precipitation and temperature, and the anticipated phenological development of planted species, existing desirable vegetation, and resident weeds. The general objective is to get seeds in the ground before the most favorable season for plant establishment (Plummer *et al*., 1968; Roundy and Call, 1988; Monsen and Stevens, 2004). The following serve as examples from rangelands in the western USA. Spring is generally the most favorable establishment period in Mediterranean-coastal and semi-arid interior rangelands that are subject to significant summer drought (Douglas *et al*., 1960; Nord *et al*., 1971; Harris and Dobrowolski, 1986). The summer monsoon is a critical establishment period in many arid desert environments (Jordan, 1981; Abbot and Roundy, 2003; Hereford *et al*., 2006). Plant establishment generally occurs in late-spring through early summer in relatively more moderate precipitation zones in the Great Plains (Robertson and Box, 1969; Hart and Dean, 1986; Ries and Hofmann, 1996) and late-spring through early fall in some higher elevation mountain sites (Hull, 1966; Lavin *et al*., 1973). Post-planting microclimate must be favorable for initial germination and emergence, but also needs to remain favorable during the vulnerable period of seedling establishment (Hyder *et al*., 1971; McGinnies, 1973; Frasier *et al*., 1987; Abbot and Roundy, 2003; James *et al*., 2011).

Dormant-fall seeding is a commonly recommended practice in the Intermountain West, USA. This practice places seeds in the ground well in advance of the optimal growing season to take advantage of all opportunities for germination, emergence, and growth during favorable periods in the winter and spring (Plummer *et al*., 1968; Nelson *et al*., 1970; Hart and Dean, 1986; Monsen and Stevens, 2004). Dormant-fall seeding is also recommended when wet spring weather precludes the use of mechanical seeding equipment and to mitigate effects of unpredictable spring weather (McGinnies, 1973; Hart and Dean, 1986). The timing of seeding may also be dependent on seasonal patterns of weed establishment and timing requirements of essential weed control measures (Robocker *et al*., 1965; Klomp and Hull, 1972). Eiswerth and Shonkwiler (2006) conducted meta-analysis of a large number of rangeland seedings and confirmed the relative benefits of fall/winter-dormant seeding on interior rangeland locations in

Nevada, USA. Very few experimental studies of seeding-season effects, however, are replicated in more than 1 or 2 years (Hull, 1948, 1974; Douglas *et al*., 1960; Robocker *et al*., 1965; Ries and Hofmann, 1996). Fall-dormant planting was found to be superior to spring planting in 73% of the individual studies reviewed by Hardegree *et al*. (2011) for rangeland seeding in the Great Basin, USA, although the majority of these studies were conducted in years of relatively favorable precipitation. Early emerging seedlings can take advantage of favorable conditions, but are also more vulnerable to periods of drought, extreme cold, and other mortality factors (James *et al*., 2011).

Seedbed preparation and planting methods often include strategies to reduce competition for water by undesirable plants (Gonzalez and Dodd, 1979; Ott *et al*., 2003; Mangold *et al*., 2007). Cheatgrass (*Bromus tectorum* L.) is a dominant annual weed that has invaded millions of hectares of rangeland in the Intermountain West, USA (Knapp, 1996). Water availability in the seedbed is greatly affected by competition from cheatgrass (Fig. 6.2), which is relatively more efficient than native perennial grasses for both initial establishment and subsequent resource utilization under conditions of water stress, and when soil temperatures are low in the fall, winter, and early spring (Harris and Wilson, 1970; Harris, 1977; Melgoza *et al*., 1990; Roundy *et al*., 2007; Hardegree *et al*., 2010). Chemical or mechanical weed control is frequently necessary for successful establishment of desirable plant species in areas that are affected by invasive weeds (e.g. Evans and Young, 1978; Humphrey and Schupp, 2002; Mangold *et al*., 2007). Hardegree *et al*. (2011) observed that out of 52 rangeland seeding studies surveyed that included an evaluation of weed control treatments, all but two concluded that weed control was either necessary, or at least beneficial to successful establishment.

Assessment, Monitoring, and Adaptive Management Tools

State-and-transition probabilities and assessment of weather variability

The need for rangeland restoration begins with a perception that an existing vegetation state is undesirable relative to some

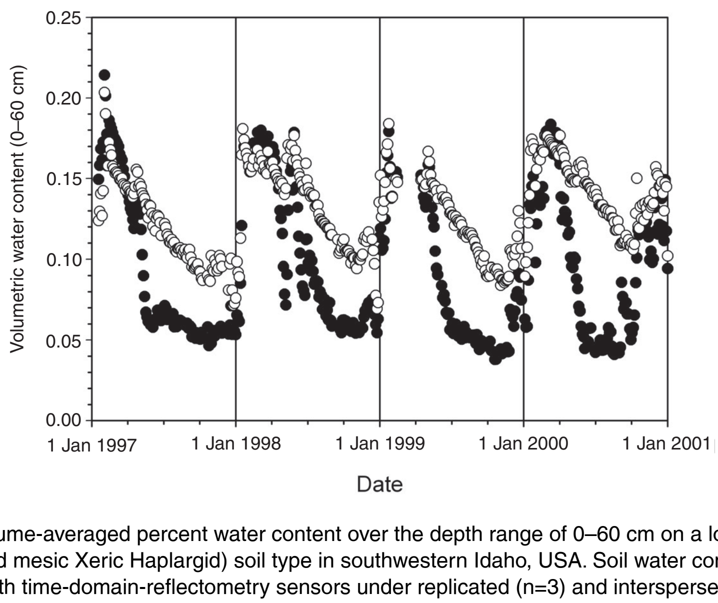

Fig. 6.2. Volume-averaged percent water content over the depth range of 0–60 cm on a loamy-sand (sandy, mixed mesic Xeric Haplargid) soil type in southwestern Idaho, USA. Soil water content was measured with time-domain-reflectometry sensors under replicated (n=3) and interspersed bare soil (open circles) and cheatgrass (closed circles) cover plots.

alternative state. Ecological site descriptions utilize state-and-transition models to define the range of vegetation states that currently exist, that may develop after additional site disturbance, or that may be achievable through management (see Brown and Bestelmeyer, Chapter 1, this volume). Current state-and-transition models acknowledge that the potential trajectories between undesirable and desirable states are limited by weather variability and that some transition pathways may require a specific and perhaps infrequent series of climatic events before a successful change in state can occur (Westoby *et al*., 1989; Batabyal and Godfrey, 2002; Bestelmeyer *et al*., 2003; Briske *et al*., 2008).

Figure 6.3 shows a simplified schematic of alternative states and transition pathways

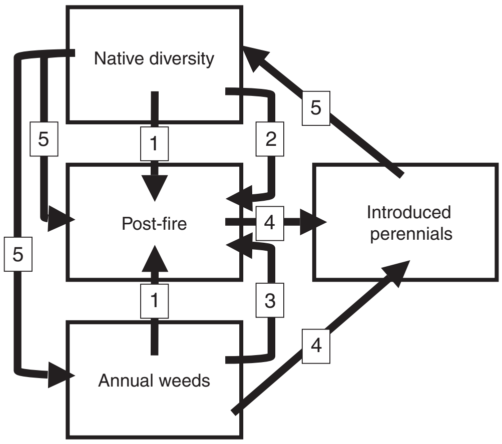

Fig. 6.3. State-and-transition model for sagebrush-bunchgrass rangeland in southern Idaho, USA that has been disturbed by introduced annual weeds. Transition 1 represents fire events, which can happen in any given year. Transition 2 represents natural recovery of native plant diversity in the absence of introduced annual weeds. Transition 3 represents type conversion if introduced weed seeds are present. Transition 4 represents a transition to an introduced perennial grass community, which may be possible only in moderate to favorable precipitation years. Transition 5 represents a transition to a diverse native community that may be possible only in favorable precipitation years with annual weed control (if necessary).

for the example of sagebrush-steppe vegetation in the Great Basin region, USA. This vegetation type historically maintained a disturbance cycle with a period of 60–100 years that included wildfire, and a post-fire successional sequence that moved through a native bunchgrass phase, and increasing shrub component (Wyoming big sagebrush; *Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle and Young). Introduced annual grasses, such as cheatgrass, have disrupted this system over millions of hectares resulting in a 5–10 year cycle of wildfire followed by immediate and persistent annual weed cover. Cheatgrass can be expected to establish adequately on most sites and most years on sagebrush-steppe rangeland (Roundy *et al*., 2007), therefore, the fire/cheatgrass cycle represented in Fig. 6.3 is relatively robust under almost any weather scenario.

Sheley *et al*. (2011) discuss the initial evaluation of undesirable site conditions, and the use of rangeland health assessment to identify the ecological processes in need of repair (Pyke *et al*., 2002). We recommend that an additional tool for initial assessment be the evaluation of historical weather variability. This variability may provide valuable perspective on the probability that proposed management actions will have the desired effect on a given ecological process in any given year.

A minimal evaluation of weather should include an assessment of mean annual and monthly patterns of precipitation and temperature. Information on climatological means will be necessary for selection of appropriate plant materials, and will define the seasonality of conditions favorable for plant establishment and growth. Climatological means also will provide baseline conditions for interpreting deviation from average conditions in any given establishment year. Annual variability can be assessed by organizing and ranking historical data of the type displayed in Fig. 6.1 for the Boise precipitation record. Ranking can be used to assess where a given year falls in the spectrum of potential weather conditions and is especially useful in interpreting the relative success of previous management actions.

Monitoring and adaptive management

Monitoring is a critical part of ecologically based restoration planning as most management actions involve a relatively high degree of uncertainty (Sheley *et al.*, 2010). This uncertainty is exacerbated by weather variability, and a general lack of information on how weather impacts the relative success of alternative management strategies. Most individual studies in the range planting literature are insufficiently replicated to extract valid inferences about weather effects (Hardegree *et al.*, 2011). The majority of range planting studies, until fairly recently, have not measured critical environmental factors affecting success, such as soil temperature and water relations, but only report relative treatment effects (Call and Roundy, 1991; Vargas *et al.*, 2001). Range planting studies also tend to extrapolate results obtained from atypical sites and weather conditions over larger areas (Cox and Martin, 1984), and are seldom replicated in multiple seeding years to account for inter-annual weather variability (Casler, 1999). It is logistically difficult to obtain field data that replicates inter-annual variability. Unfortunately, previous studies do not include enough commonality in experimental design features to be subject to any detailed meta-analysis of general weather effects (Durlak and Lipsay, 1991; Michener, 1997; Osenberg *et al.*, 1999; Gurevitch *et al.*, 2001). It may be possible to develop guidelines, however, for establishing some common experimental design features for future studies that may be amenable to more sophisticated meta-analysis.

The stochastic nature of weather variability may require adoption of new paradigms for monitoring and evaluating alternative management strategies. Specifically, both restoration failure and success must be evaluated in the context of weather conditions during the period of establishment. Adaptive management alternatives should be viewed in the context of weather ranking during the establishment season being evaluated. If the seasonal conditions were significantly below average, it may not be necessary to abandon strategies that did not seem to work in that particular year. Lessons learned from successful management actions should also be weighed in the context of relative favorability in weather in that year. Multi-year evaluation should be considered when comparing alternative management treatments, and multi-year treatments may be necessary to achieve acceptable levels of establishment success at a given site.

Long-term weather forecasting opportunities

The most useful potential technology for enhancing establishment success lies in development and utilization of relatively long-range weather forecast technology specific to rangeland planting applications (e.g. Barnston *et al.*, 2000, 2005; Garbrecht and Schneider, 2007; Lim *et al.*, 2011). Similar technology is in relatively common use for more traditional agricultural applications (Doblas-Reyes *et al.*, 2006; Baigorria *et al.*, 2008; O'Lenic *et al.*, 2008). Long-term weather forecasts in many rangeland areas are often merely synoptic descriptions of historical weather patterns and not based on physical or empirical prediction of future weather conditions. Even low-resolution weather forecasts, however, would increase the probability of successful native plant establishment if management decisions at the time of seeding could be based on the anticipation of favorable conditions for seed germination, emergence, and seedling establishment (Hardegree *et al.*, 2003; Hardegree and Van Vactor, 2004). Weather forecasts could be used to initiate contingency plans in areas that have been previously identified for restoration, and for which pre-management logistics of equipment, personnel, and plant materials are in place (Westoby *et al.*, 1989; Bakker *et al.*, 2003).

Currently available long-term forecast information is probabilistic in format. Probability of Exceedance (PoE) distributions define the potential deviation of future weather conditions (typically over seasons) from the long-term mean (Barnston *et al.*, 2000; Schneider and Garbrecht, 2006; Garbrecht and Schneider, 2007; Lim *et al*., 2011). In simpler terms, the forecasts predict the odds for whether the weather will shift toward wetter or drier, warmer or cooler, when compared to the reference period of record. These predictions apply to relatively large spatial domains and are currently subject to relatively high predictive errors for many parts of the globe. Long-term forecast predictions work better in some areas than others and are generally more accurate for temperature than for precipitation (Schneider and Garbrecht, 2006; Livezey and Timoveyeva, 2008; Lim *et al*., 2011). In the USA, predictive accuracy is relatively higher where extreme weather events and sustained deviations from average are associated with the El Niño Southern Oscillation (ENSO) phenomenon. Long-term weather predictions in the USA are relatively more accurate in the southeast, southern Texas, desert southwest, California, Pacific Northwest, and northern Rocky Mountains, but are relatively less accurate in the Intermountain Great Basin. Other areas of the world, particularly tropical regions in or adjacent to the Pacific Ocean, enjoy a stronger and more reliable predictive signal. The Australian Government Bureau of Meteorology has developed a successful forecast system for ENSO-related impacts on agriculture and water resources in eastern and southern Australia (Lim *et al*., 2011).

Weather and climate data resources

It can be challenging to locate accurate, continuous, long term, site-specific weather data. Much of the data available over the internet has not been quality assured, or may be a derivative product representing data averaged or interpolated over large areas.

The global database for historical weather data can be accessed through the US Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Climate Data Center website (www.ncdc.noaa.gov/oa/ncdc.html). This site is the repository for US weather information, but also has links to global weather resources, including the World Meteorological Organization that maintains a list of meteorological data sources by country (www.wmo.int/pages/members/members_en.html). NOAA has also been developing Regional Climate Centers that consolidate state weather and climate data (www.ncdc.noaa.gov/oa/climate/regionalclimatecenters.html), and can frequently provide advice on data access and quality assurance questions.

Many field sites will not have sufficient local information for detailed characterization of site variability. Some areas will have additional regional resources for interpolating weather records in areas that do not have local monitoring. Interpolated data will not be as accurate as actual observations but may be sufficient for many practical applications. Tools and databases for interpolation of historical weather data are available in much of the USA through sites such as the DAYMET US Data Center, which is provided by the Montana State University, Numerical Terradynamic Simulation Group (www.daymet.org/default.jsp) and the USDA Natural Resources Conservation Service National Water and Climate Center (www.wcc.nrcs.usda.gov/climate/prism.html).

Long-term (covering weeks to multiple months) weather forecast information is increasingly available in many countries. These forecasts are created through ensemble analysis of multiple global climate models, and analysis of statistical relationships between weather and oceanic state (e.g. ENSO) in different parts of the globe (Barnston *et al*., 2000, 2005; Lim *et al*., 2011). Many nations and nation groups have developed, or are developing, regional predictive capabilities such as the European Centre for Medium-Range Weather Forecasts (www.ecmwf.int). Long-term forecasts for precipitation and temperature for Australia are available through the Australian Bureau of Meteorology (www.bom.gov.au/climate/ahead), and for much of the globe through the International Research Institute for Climate and Society (http://portal.iri.columbia.edu/portal/server.pt/). The principal repository of long-term forecast data and information in the USA is the NOAA National Weather Service's Climate Prediction Center (www.cpc.ncep.noaa.gov).

Incorporating weather variability and long-term forecasts in rangeland restoration efforts

As a first step, assessment of historical weather variability should be made for the rangeland site of interest. Monthly total precipitation and average daily air temperature are relatively easy to obtain and are sufficient to provide a baseline for assessing rangeland restoration options, and for considering the possible use of long-term forecasts. The World Meteorological Organization produces a product representing the most recent 30-year period, revised every decade (currently 1981–2010). It is highly desirable to find the most local monthly data possible, or barring that, a good interpolation for the area of interest, for these 30 years. Once obtained, monthly, seasonal, and annual data can be totaled (precipitation) and averaged (air temperature) to establish baseline data for ranking of current and historical time periods relative to average conditions for a given time period.

Forecasting applications are generally applied to 3-month intervals rather than individual monthly predictions (e.g. January–February–March, February–March–April, etc.). It is critical to understand that forecasts are probabilistic predictions and subject to relatively large errors. The authors recommend considering only those precipitation or air temperature forecasts predicting a shift in odds of at least 8% (Schneider and Garbrecht, 2006), with more serious consideration for larger forecast shifts, especially during moderate to strong ENSO conditions. Such strong forecasts are rarely offered for precipitation but may represent a reasonable guide for the efficient expenditure of rangeland restoration resources when they do occur.

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