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Weather Tools for Retrospective Assessment of Restoration Outcomes[☆]

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ABSTRACT

Rangeland seeding practices in the Intermountain western United States are predominantly implemented in the year immediately following wildfire for the purposes of Emergency Stabilization and Rehabilitation (ESR). This necessarily links restoration and rehabilitation outcomes to the probability of a single year providing sufficiently favorable microclimatic conditions for desirable plant establishment. Field research studies in rangeland restoration are also typically of limited duration, and published results may not represent the full spectrum of conditions likely to be experienced at a given site. We propose that location-specific and temporal weather analysis may enhance the interpretation of historical planting data, support expanded inferences from short-term field studies, and facilitate meta-analysis of diverse field studies in rangeland restoration. We describe access and use of new databases and tools that can be used to characterize and rank weather and soil-microclimatic variables and suggest some standard graphs and weather metrics to establish a longer-term perspective for the interpretation of rangeland restoration outcomes. Tools of this type may also be useful in the interpretation of a wide range of agricultural and natural resource applications that are driven by similar weather inputs, particularly in arid and semiarid systems that exhibit high annual and seasonal variability in precipitation and temperature.

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Introduction

Millions of hectares of rangelands in the western United States are undergoing type conversion to invasive annual and woody species (Davies, 2008; Johnson and Miller, 2008; Germino et al., 2016). Western rangelands have an arid or semiarid climate and exhibit high variability in seasonal and annual weather (Hardegree et al., 2012a, 2012b). A high probability of unfavorable site conditions generally results in unacceptable restoration outcomes regardless of the choice of species, planting technique, or seedbed preparation treatment (Hardegree et al., 2011). Rangeland seeding studies are generally of insufficient duration to adequately survey potential variability in seedbed microclimate at a given field site (Casler, 1999), and the scientific literature on the subject is biased toward years with above-average precipitation (Hardegree et al., 2011). High seasonal and interannual weather variability greatly complicates the interpretation of research results and the prospects for using single-year field studies to inform future treatment recommendations under adaptive management guidelines (Hardegree et al., 2012a, 2012b; Monaco et al., 2016).

The soil microclimatic conditions necessary for the initial establishment of desirable range plants may occur infrequently in highly disturbed rangeland systems (Westoby et al., 1989; Call and Roundy, 1991; Peters, 2000; Hardegree et al., 2011). It is perhaps unreasonable to expect a fully successful restoration outcome in any specific year and, therefore, inappropriate to derive general management recommendations from short-term field studies (Hardegree et al., 2011). Single-year seeding events in the year immediately following wildfire, however, remain the primary management treatment in response to

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annual grass invasion and dominance (Eisworth and Shonkwiler, 2006; Eisworth et al., 2009; Kulpa et al., 2012; Pyke et al., 2013). Site and year-specific weather information, as well as a historical perspective of weather variability at a site, may be useful in the development of long-term restoration management plans that have a realistic expectation of success (Hardegree et al., 2012a, 2012b).

Recent studies have suggested that postgermination and pre-emergence mortality from relatively short-term temperature or drought stress are principal bottlenecks for establishment of many perennial grasses (James et al., 2011; Boyd and Lemos, 2013; Hardegree et al., 2016). Hardegree et al. (2003, 2013) characterized annual variability in seedbed favorability for germination but subsequently modified these descriptions to include an assessment of postgermination mortality events that could affect seedling emergence and establishment (Hardegree et al., 2016). The seasonality of potential frost damage has historically been a major determinant of planting date for many crop species (Anapalli et al., 2005). Avoidance of seasonal mortality events has also provided a functional explanation for the evolution of seed dormancy mechanisms in many wildland species (Finch-Savage and Leubner-Metzger, 2006). Assessment of potential postgermination/pre-emergence mortality should be considered when developing expectations for individual-year treatment effects on seedling establishment (Hardegree et al., 2016).

In this paper, we describe a restoration-climatology report that can be used to identify seasonal weather and microclimatic conditions that drive individual site-year responses to rangeland restoration treatments. Data summary and analysis tools are linked to a gridded weather dataset (Abatzoglou, 2013) that can be used for retrospective analyses of field studies, expansion of inference from what are typically relatively short-term field experiments, and meta-analyses of previous and future rangeland planting studies. The long-term nature of this dataset allows for the interpretation of single field events within the context of potential site variability, as well as to develop probabilistic expectations for the success of long-term, iterative, adaptive management plans.

Database, Modeling, and Climatology-Report Generation

We developed a website in cooperation with the Joint Fire Science Program, Great Basin Fire Science Exchange that can be accessed through their website (http://greatbasinfirescience.org) or directly (http://greatbasinweatherapplications.org) for a number of weather-centric restoration planning and analysis tools. In addition to site-specific climatological information, this site provides a bibliographic database of journal articles related to weather impacts on rangeland plant establishment and a number of educational modules for university-level laboratory exercises in weather-centric rangeland restoration planning.

Site-specific restoration information is accessed by filling out a web form with site location (latitude and longitude) surface soil texture and contact information for the recipient of the output. Three products are currently available for download: a data file with estimated daily weather parameters for the site location for the period 1 January 1979 through present (Abatzoglou, 2013); a data file with estimated hourly temperature and water availability at 2-cm soil depth for the same time period (Flerchinger and Hardegree, 2004; Flerchinger et al., 2012); and a restoration-climatology report that synthesizes annual and seasonal information on both seedbed favorability for establishment (Hardegree et al., 2003, 2013) and potential risk from postgermination/pre-emergence mortality from freezing and drought (Hardegree et al., 2016).

The historical weather file is derived from the gridded meteorological database (gridMET) developed by Abatzoglou (2013) to support ecological modeling applications. The gridMET database contains daily weather variables for the conterminous United States from 1979 to present at a spatial resolution of approximately 4 km. GridMET is updated daily and resides in NetCDF format on the University of Idaho Northwest Knowledge Network server (http://climate.nkn.uidaho.edu/METDATA/).

The historical weather file that we automatically extract from gridMET with our web form consists of a period-of-record time series of weather information for the following parameters: precipitation (mm), air temperature (minimum, maximum; °C), mean humidity (dew point; °C), mean wind speed (ms^{-1}), and mean solar radiation (downward short wave; Wm^{2}). We make these core data available for users who want the flexibility to conduct their own site analysis of weather variability, but we also use the data for modeling seedbed microclimate and to develop climatological syntheses for the report output.

The website automatically takes the long-term site weather file and soil information and estimates an hourly time series of seedbed water potential (MPa) and soil temperature (°C) at 2-cm depth using the Simultaneous Heat and Water (SHAW) model as described previously by Flerchinger and Hardegree (2004), Flerchinger et al. (2012), and Hardegree et al. (2003, 2013). Individual year and seasonal distributions of near-surface soil freezing (soil temperatures ≤ 0°C) and drought (soil water potential ≤ −1.5 MPa) are then extracted from the model output using procedures described by Hardegree et al. (2016). This time series is also available for direct download for users who want to conduct a more detailed analysis of potential seedbed conditions for both germination and postgermination mortality events.

The rangeland restoration climatology report is currently customized for Great Basin rangeland-restoration scenarios that involve fall seeding on bare-ground sites in the year following wildfire. We use the hydrologic year (HY) convention for characterizing weather and seedbed microclimate with each HY beginning on 1 October and running through 30 September. The year designation for each HY refers to the calendar year in which the HY ends. The report cover page indicates when the report was generated, information about the site location and surface soil texture, the location of the gridMET node used for weather-data extraction, and the time period spanned in the weather data. The body of the report consists of a brief introduction; graphical and tabular representations of seasonal patterns of temperature and precipitation (Fig. 1); interannual variability in precipitation; and an annual ranking of precipitation as a function of HY, initial establishment season (October — June), spring growth and establishment period (March — May; Fig. 2), and individual months. Each HY is also represented by a graph of total monthly precipitation and percent-of-average precipitation to identify intra-annual patterns of precipitation and drought for specific planting years (Fig. 3a). Seasonal distributions of potential freezing and drought events are also presented in both the HY summary pages (Fig. 3b) and a graph of long-term seasonal averages (Fig. 4).

The examples presented in the figures were drawn from a report generated for a site southeast of Boise, Idaho (43.32 N, 115.98 W) for the sandy loam soil (72% sand, 22% silt, 6% clay) characterized by

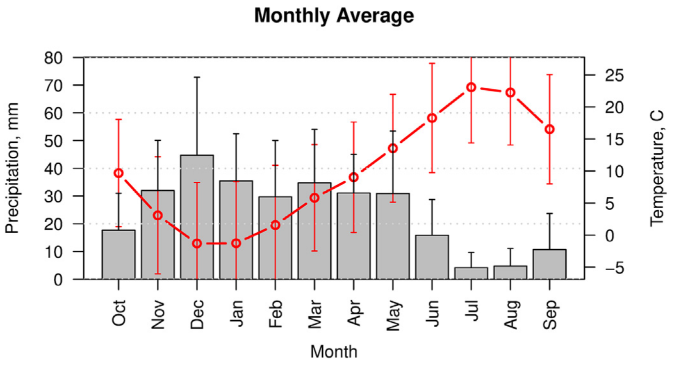

Figure 1. Monthly temperature and precipitation for the Orchard field test location southeast of Boise, Idaho, United States (43.32 N, 115.98 W) for the period 1 January, 1979 to 30 September, 2015). Error bars represent 1 standard deviation above the mean.

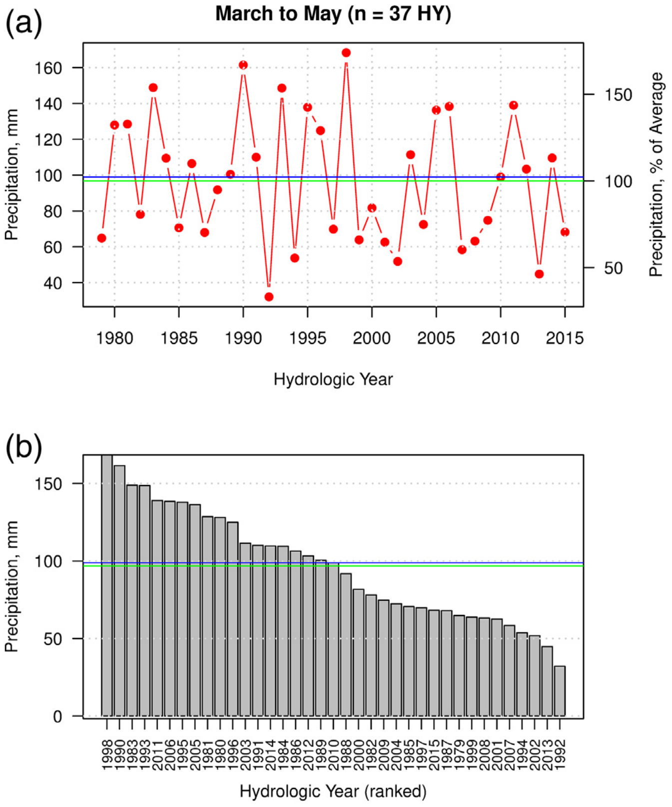

Figure 2. Interannual variation in cumulative March – May precipitation from 1979 to 2015 for the Orchard field test location southeast of Boise, Idaho, United States (43.32 N, 115.98 W) (**a**) and ranked cumulative precipitation in descending order of amount (**b**). Green horizontal line marks the mean and the blue horizontal line marks the median precipitation for the period of record.

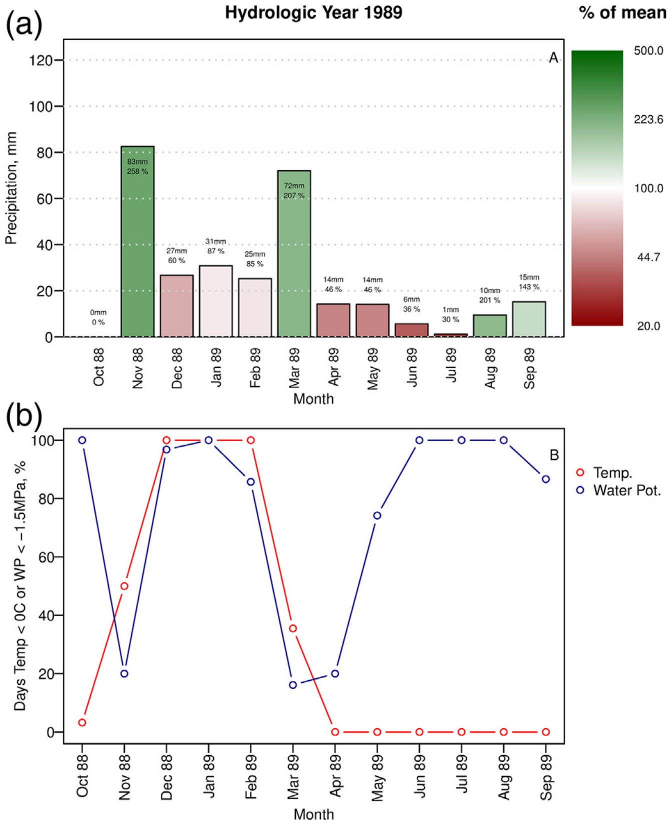

Figure 3. Monthly pattern of precipitation (mm) for hydrologic year (October 1988 – September 1989) at the Orchard field test location southeast of Boise, Idaho, United States (43.32 N, 115.98 W) (**a**) and percent of normal for the period of record (color coding), as well as the percentage of days with at least 1 hr below temperature (0°C) or water potential (− 1.5 MPa) thresholds (**b**).

Flerchinger et al. (2012). This site has a typical annual-precipitation and temperature profile for the northern Great Basin sagebrush steppe, with precipitation falling predominantly in the winter and spring, low winter temperatures, and high temperatures and drought through the summer (see Fig. 1). Precipitation in this region, however, is highly variable from year to year during periods critical for establishment and seedling growth (see Figs. 1 and 2). The distribution of both freezing and drought conditions in the seedbed is also highly variable from year to year (see Figs. 3b and 4). This variability typically results in a fairly unique profile of weather and seedbed microclimate in any individual planting season that may contain more information for interpretation of restoration outcomes than can be obtained solely from the seasonal precipitation average (see Fig. 3). In our example, the March to May period in 1989 was near the long-term mean for precipitation (see Fig. 2), but a more detailed assessment shows a relatively wet November, followed by a dry and cold winter, a relatively wet March, and spring drought in April and May (see Fig. 3). In this year, the possibilities exist for significant seedling mortality: from high fall germination in November, followed by postgermination frost mortality during the winter; and significant postemergence drought in the spring. Using this example for retrospective assessment of an individual seeding or field study, it would be possible to classify this year relative to the full spectrum of weather conditions possible at the site.

Potential Applications

The proposed utility of these tools includes both science and management applications. The Land Treatment Digital Library (LTDL; http://ltdl.wr.usgs.gov/) includes data from historical Bureau of Land Management plantings in the Intermountain western United States. The LTDL has been previously analyzed for rangeland seeding outcomes, but not specifically related to weather variability in the year of initial establishment (Arkle et al., 2014; Knutson et al., 2014). The analysis tool described in this paper could be used to evaluate weather effects from these past plantings or specific weather conditions during any past management activity or published field study (Hardegree et al., 2011).

Ecological site descriptions (ESDs) are a key resource in the implementation of Natural Resources Conservation Service (NRCS) conservation plans, and these tools are also a primary resource for rangeland restoration planning and management (Bestelmeyer et al., 2003; Stringham et al., 2003; Herrick et al., 2006; Caudle et al., 2013; NRCS, 2013). ESDs include state-and-transition models (STMs) that describe potential alternative vegetation states at a given site and attempt to address transition probabilities for crossing thresholds between states (Briske et al., 2005, 2006). The tools we describe in this paper could be used as an ESD supplement for information about probabilistic weather effects and could yield useful information in understanding transition probabilities and the likelihood of conditions suitable for successful establishment of desirable plants.

Most field studies on the subject of rangeland restoration, and indeed in almost any agricultural or natural resource application, are of limited duration due to logistical and budgetary constraints (Casler, 1999; Hardegree et al., 2011. This imposes significant inference limitations for analysis of these short-term studies, but the relevance of individual site treatments could perhaps be extended by evaluating them in the context of long-term expectations for site weather and seedbed microclimate (Hardegree and Van Vactor, 2000). We recommend that future rangeland restoration studies include graphs showing the ranking of the experimental year within the historic range of climatic variability during the planting season and the seasonal progression of precipitation and potential postgermination mortality events during

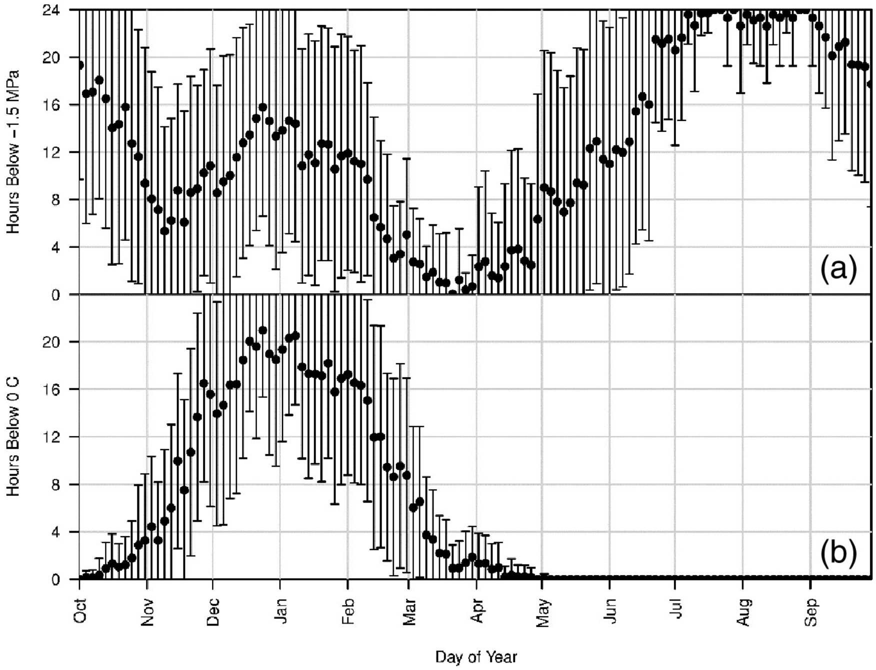

Figure 4. Seasonal pattern of the mean number of hours per day below temperature (**a**) and water potential (**b**) thresholds for days with at least 1 hr below 0°C or −1.5 MPa for the Orchard field test location southeast of Boise, Idaho, United States (43.32 N, 115.98 W) using data from 1979 to 2015. Error bars represent ± 1 standard deviation.

the experimental period (Hardegree et al., 2012b, 2016; see Figs. 2-4). Tabular data with this information could also provide a standard context for meta-analysis of historical field studies (Hardegree et al., 2011).

Numerous field studies have used process-based and empirical models for evaluating weather effects on hydrologic processes (Al-Hamdan et al., 2015; Rathjens et al., 2015; Williams et al., 2016), seedbed microclimate (Hardegree et al., 2013; Bullied et al., 2014b, 2014a), and agricultural and grazing land productivity (Nielsen et al., 2012; Fang et al., 2014; Ma et al., 2016). The underlying database and data access tools described in this paper could potentially be used to generate input data for any agricultural or natural resource application that is driven by similar daily weather data or that requires weather information in locations without meteorological infrastructure (Abatzoglou, 2013).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rama.2018.10.011.

References

Abatzoglou, J.T., 2013. Development of gridded surface meteorological data for ecological applications and modeling. International Journal of Climatology 33, 121–131.

Al-Hamdan, O.Z., Hernandez, M., Pierson, F.B., Nearing, M.A., Williams, C.J., Stone, J.J., Boll, J., Weltz, M.A., 2015. Rangeland hydrology and erosion model (RHEM) enhancements for applications on disturbed rangelands. Hydrology Process 29, 445–457.

Anapalli, S.S., Ma, L., Nielsen, D.C., Vigil, M.F., Ahuja, L.R., 2005. Simulating planting date effects on corn production using RZWQM and CERES-maize models. Agronomy Journal 97, 58–71.

Arkle, R.S., Pilliod, D.S., Hanser, S.E., Brooks, M.L., Chambers, J.C., Grace, J.B., Knutson, K.C., Pyke, D.A., Welty, J.L., Wirth, T.A., 2014. Quantifying restoration effectiveness using multi-scale habitat models: implications for sage-grouse in the Great Basin. Ecosphere 5, 31.

Bestelmeyer, B.T., Brown, J.R., Havstad, K.M., Alexander, R., Chavez, G., Herrick, J., 2003. Development and use of state-and-transition models for rangelands. Journal of Range Management 56, 114–126.

Boyd, C.S., Lemos, J.A., 2013. Freezing stress influences emergence of germinated perennial grass seeds. Rangeland Ecology & Management 66, 136–142.

Briske, D.D., Fuhlendorf, S.D., Smeins, F.E., 2005. State-and-transition models, thresholds, and rangeland health: a synthesis of ecological concepts and perspectives. Rangeland Ecology & Management 58, 1–10.

Briske, D.D., Fuhlendorf, S.D., Smeins, F.E., 2006. A unified framework for assessment and application of ecological thresholds. Rangeland Ecology & Management 59, 225–236.

Bullied, W.J., Bullock, P.R., Flerchinger, G.N., Van Acker, R.C., 2014b. Process-based modeling of temperature and water profiles in the seedling recruitment zone: Part II. Seedling emergence timing. Agriculture Forest Meteorology 188, 104–120.

Bullied, W.J., Flerchinger, G.N., Bullock, P.R., Van Acker, R.C., 2014a. Process-based modeling of temperature and water profiles in the seedling recruitment zone: Part 1. Model validation. Agriculture Forest Meteorology 188, 89–103.

Call, C.A., Roundy, B.A., 1991. Perspectives and processes in revegetation of arid and semiarid rangelands. Journal of Range Management 44, 543–549.

Casler, M.D., 1999. Repeated measures vs. repeated plantings in perennial forage grass trials: an empirical analysis of precision and accuracy. Euphytica 105, 33–42.

Caudle, D., Di Benedetto, J., Karl, M., Sanchez, H., Talbot, C., 2013. Interagency ecological site handbook for rangelands. USDA Natural Resources Conservation Service, Washington DC, USA 109 p.

Davies, K.W., 2008. Medusahead dispersal and establishment in sagebrush steppe plant communities. Rangeland Ecology & Management 61, 110–115.

Eiswerth, M.E., Shonkwiler, J.S., 2006. Examining post-wildfire reseeding on arid rangeland: a multivariate tobit modelling approach. Ecological Modeling 192, 286–298.

Eiswerth, M.E., Krauter, K., Swanson, S.R., Zielinski, M., 2009. Post-fire seeding on Wyoming big sagebrush ecological sites: regression analyses of seeded nonnative and native species densities. Journal of Environmental Management 90, 1320–1325.

Fang, Q.X., Andales, A.A., Derner, J.D., Ahuja, L.R., Ma, L., Bartling, P.N.S., Reeves, J.L., Qi, Z., 2014. Modeling weather and stocking rate effects on forage and steer production in northern mixed-grass prairie. Agriculture Systems 129, 103–114.

Finch-Savage, W.E., Leubner-Metzger, G., 2006. Seed dormancy and the control of germination. New Phytology 171, 501–523.

Flerchinger, G.N., Hardegree, S.P., 2004. Modelling near-surface soil temperature and moisture for germination response predictions of post-wildfire seedbeds. Journal of Arid Environments 59, 369–385.

Flerchinger, G.N., Caldwell, T.G., Cho, J., Hardegree, S.P., 2012. Simultaneous heat and water (SHAW) model: model use, calibration, and validation. Transactions of the ASABE 55, 1395–1411.

Germino, M.J., Belnap, J., Stark, J.M., Allen, E.B., Rau, R.N., 2016. Ecosystem impacts of exotic annual invaders. In: Germino, M.J., Chambers, J.C., Brown, C.S. (Eds.), Exotic brome grasses in arid and semiarid ecosystems of the western US: causes, consequences, and management implications. Springer International Publishing, Basel, Switzerland, pp. 61–95.

Hardegree, S.P., Van Vactor, S.S., 2000. Germination and emergence of primed grass seeds under field and simulated-field temperature regimes. Annals of Botany 85, 379–390.

Hardegree, S.P., Flerchinger, G.N., Van Vactor, S.S., 2003. Hydrothermal germination response and the development of probabilistic germination profiles. Ecological Modelling 167, 305–322.

Hardegree, S.P., Schneider, J.M., Moffet, C.A., 2012a. Weather variability and adaptive management for rangeland restoration. Rangelands 34 (53), 56.

Hardegree, S.P., Moffet, C.A., Flerchinger, G.N., Cho, J., Roundy, B.A., James, J.J., Clark, P.E., Pierson, F.B., 2013. Hydrothermal assessment of temporal variability in seedbed microclimate. Rangeland Ecology & Management 66, 127–135.

Hardegree, S.P., Sheley, R.L., Duke, S.E., James, J.J., Boehm, A.R., Flerchinger, G.N., 2016. Temporal variability in microclimatic conditions for grass germination and emergence in the sagebrush steppe. Rangeland Ecology & Management 69, 123–128.

Hardegree, S.P., Cho, J., Schneider, J.M., 2012b. Weather variability, ecological processes, and optimization of soil micro-environment for rangeland restoration. In: Monaco, T.A., Sheley, R.L. (Eds.), Invasive plant ecology and management: linking processes to practice. CAB International, Wallingford, Oxon, pp. 107–121.

Hardegree, S.P., Jones, T.A., Roundy, B.A., Shaw, N.L., Monaco, T.A., 2011. Assessment of range planting as a conservation practice. In: Briske, D.D. (Ed.), Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps. Allen Press, Lawrence, KS, USA, pp. 171–212.

Herrick, J.E., Bestelmeyer, B.T., Archer, S., Tugel, A.J., Brown, J.R., 2006. An integrated framework for science-based arid land management. Journal of Arid Environments 65, 319–335.

James, J.J., Svejcar, T.J., Rinella, M.J., 2011. Demographic processes limiting seedling recruitment in arid grassland restoration. Journal of Applied Ecology 48, 961–969.

Johnson, D.D., Miller, R.F., 2008. Intermountain presettlement juniper: distribution, abundance, and influence on postsettlement expansion. Rangeland Ecology & Management 61, 82–92.

Knutson, K.C., Pyke, D.A., Wirth, T.A., Arkle, R.S., Pilliod, D.S., Brooks, M.L., Chambers, J.C., Grace, J.B., 2014. Long-term effects of seeding after wildfire on vegetation in Great Basin shrubland ecosystems. Journal of Applied Ecology 51, 1414–1424.

Kulpa, S.M., Leger, E.A., Espeland, E.K., Goergen, E.M., 2012. Postfire seeding and plant community recovery in the Great Basin. Rangeland Ecology & Management 65, 171–181.

Ma, L., Ahuja, L.R., Trout, T.J., Nolan, B.T., Malone, R.W., 2016. Simulating maize yield and biomass with spatial variability of soil field capacity. Agronomy Journal 108, 171–184.

Monaco, T.A., Hardegree, S.P., Pellant, M., Brown, C.S., 2016. Assessing restoration and management needs for ecosystems invaded by exotic annual *Bromus* species. In: Germino, M.J., Chambers, J.C., Brown, C.S. (Eds.), Exotic brome grasses in arid and semiarid ecosystems of the western US: causes, consequences, and management implications. Springer International Publishing, Basel, Switzerland, pp. 339–370.

Nielsen, D.C., Saseendran, S.A., Ma, L., Ahuja, L.R., 2012. Simulating the production potential of dryland spring canola in the central Great Plains. Agronomy Journal 104, 1182–1188.

NRCS (Natural Resources Conservation Service), 2013. Ecological site description (ESD) system for rangeland and forestland. Available at:. https://esis.sc.egov.usda.gov/Welcome/pgESDWelcome.aspx.

Peters, D.P.C., 2000. Climatic variation and simulated patterns in seedling establishment of two dominant grasses at a semi-arid-arid grassland ecotone. Journal of Vegetation Science 11, 493–504.

Pyke, D.A., Wirth, T.A., Byers, J.L., 2013. Does seeding after wildfires in rangelands reduce erosion or invasive species? Restoration Ecology 21, 415–421.

Rathjens, H., Oppelt, N., Bosch, D.D., Arnold, J.G., Volk, M., 2015. Development of a grid-based version of the SWAT landscape model. Hydrology Process 29, 900–914.

Stringham, T.K., Krueger, W.C., Shaver, P.L., 2003. State and transition modeling: an ecological process approach. Journal of Range Management 56, 106–113.

Westoby, M., Walker, B., Noy-Meir, I., 1989. Opportunistic management for rangelands not at equilibrium. Journal of Range Management 42, 266–274.

Williams, C.J., Pierson, F.B., Spaeth, K.E., Brown, J.R., Al-Hamdan, O.Z., Weltz, M.A., Nearing, M.A., Herrick, J.E., Boll, J., Robichaud, P.R., Goodrich, D.C., Heilman, P., Guertin, D.P., Hernandez, M., Wei, H., Hardegree, S.P., Strand, E.K., Bates, J.D., Metz, L.J., Nichols, M.H., 2016. Incorporating hydrologic data and ecohydrologic relationships into ecological site descriptions. Rangeland Ecology & Management 69, 4–19.