SECTION 1. ADMINISTRATIVE INFORMATION:

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· Project title**: Improving the Success of Post-Fire Adaptive Management Strategies in Sagebrush Steppe**

· Agreement number: N.A. (funds delivered via change of allocation among USGS centers)

· Date of the report: initially submitted: 07 November 2020, revised 16 April 2021.

· Period of time covered by the report: October 2018 to present, Termination date was 7 July 2020

· Actual total cost of the project: $338,916

SECTION 2. PUBLIC SUMMARY:

Identifying the weather thresholds that can transform plant communities is key to assessing the vulnerability of ecosystems to drought and climate shifts, and thus enabling adaptive management to mitigate their impacts on land resources. We asked whether and how drought contributes to decline of big sagebrush, a widespread shrub of the western US that is critical for wildlife such as the imperiled sage grouse yet is poorly adapted to fire. Our objective was to quantitatively define "ecological drought" – water deficits that result in impacts to ecosystems - based on a precise set of weather and soil moisture conditions that are associated with failure of sagebrush stands to recover and sites converted into low-diversity grasslands prone to re-burning. Using state-of-the art downscaled weather, soil-water modeling, and robust field or remotely sensed data on sagebrush abundances for hundreds of burned and re-seeded areas over a ~25 year period, we discovered that weather conditions are indeed associated with success or failure of post-fire sagebrush seeding. Specifically, failed seedings had a week less of readily available water in the top layer of soil during March of the year after post-fire seeding, compared to sites where sagebrush recovered. However, convenient and readily available (but coarse) drought indices such as the Standardized

Precipitation-Evaporation Index (SPEI) were not able to predict the changes in sagebrush abundance. These results are significant considering that post-fire seeding of sagebrush is one of the largest restoration activities occurring on earth, yet recovery rates have historically been low. Our results help explain why seeding successes and failures may have occurred in the past and can be used to help plan when and where seedings may be more successful in the future. The findings were used in creating a drought-module tool that help managers determine the historical and future threat of drought for particular areas of restoration interest within the USGS/BLM Land Treatment Exploration Tool that is now used routinely across the Department of Interior for planning post-fire management.

SECTION 3. PROJECT SUMMARY:

We evaluated how ecological drought has affected seeding and planting outcomes in post-fire rehabilitation projects in sagebrush steppe, and then translated the information into tools that will provide key information for developing an adaptive approach to post-fire management. Post-fire seeding and planting of sagebrush and associated perennials are needed to counter the recent loss of substantial areas of sagebrush steppe. Unfortunately, their success has historically been mixed, and the failures are often attributed to sites being arid in general, but also to dry weather that seem to prevail during and after wildfires even in relatively wetter sites. This effect of dry weather and drought has not been formally evaluated until the current project.

The project revealed how water deficits combined with warmer conditions in the first years after fire have affected long-term recovery of sagebrush across a range of climate, topographic, and soil conditions. This was accomplished using two strategies for sampling sagebrush on hundreds of historic wildfires across the intermountain western U.S. that were seeded in the year after fire. We then related the sagebrush changes to seasonal weather data or weather-based simulations of soil-water availability. One sampling approach used intensive field-based measurements of sagebrush and associated plant-soil variables for >600 burned and seeded "point" locations. Recovery of sagebrush can be notoriously patchy across the large and variable areas burned each year, and so we also used an extensive gridded-model approach to obtain "wall-to-wall" estimates of sagebrush across the entirety of burned and seeded areas, many of which were >100,000 ha. The gridded estimates of sagebrush that have just become available (summer 2020) are for nearly all years from 1984-present from the USGS National Land Cover Database "Back in Time" models of Landsat satellite imagery (NLCD BIT; https://www.mrlc.gov/data?f%5B0%5D=category%3ARangeland%20-%20Historical%20Time-Series%20%E2%80%93%20BIT). Our research required an assessment of detection error in the NLCD BIT, which we formally integrated into Bayesian models of the response of long-term sagebrush cover in the weather prevailing in the first years after fire.

Long-term sagebrush recovery estimated in the field or in the NLCD BIT could not be predicted from nominal indices of "drought" (specifically SPEI, the Standardized Precipitation Evapotranspiration Index), but instead could be predicted from weather or soil-water estimates made more resolutely in time. SPEI is not designed to capture the effects of key shallow wetting or deep recharge of soil water that are critical for seedling establishment and survival of the deep-rooted sagebrush, which may underlie why post-fire recovery is unrelated to SPEI. Bayesian models of post-fire shrub establishment in the NLCD BIT that included temperature and precipitation directly (i.e., and not via a derived index like SPEI) for the particular months relevant to key demographic stages had greater predictive power.

Sagebrush recovery measured in the field was concisely predicted by the combination of quantitative estimates of soil-water in the shallow soil horizons during the time period and in the shallow soil horizons where seeds germinate and seedlings initially deploy their roots (which is March and 0-5 cm depth). In this narrow space-time "keyhole", sites where sagebrush had successful established after fires were estimated to have a mere - but critical - additional week of wet-warm soil conditions, defined specifically as soils wetter than the threshold -2.5 MPa when temperatures were above-freezing. These thresholds precisely identify "ecological drought" for post-fire recovery of big sagebrush across the vast range where fires and post-fire seeding are most common.

In addition to publications, presentations, and field tours, the technology transfer includes a digital tool kit and accompanying guide for assessing potential drought effects in planning post-fire seedings or plantings. The research and data outcomes have opened a new domain of research questions and opportunities to enable adaptive management regarding climate variability and drought impacts. Findings described herein were primarily derived from published work.

SECTION 4. REPORT BODY:

Purpose and Objectives:

Sagebrush steppe is one of the most widely distributed ecosystems in North America, but it is contracting considerably due to shifting fire behavior that accompanies exotic-grass invasion and climate shifts (reviewed in Miller et al. 2011). While sagebrush is slow to return after fire, exotic grasses are well adapted and can spread quickly in burned areas where they produce fine-textured fuels that readily reburn, ultimately converting vast swaths of sagebrush steppe to exotic-grasslands (reviewed in Germino et al. 2016). As a result, key ecosystem services including site and soil stability, forage production, and habitat for species such as sage grouse are greatly diminished (Germino et al. 2016).

In response to these threats, resource managers use post-fire treatments such as seeding and plantings in attempt to recover key native perennials, and the thousands of treatments that have been applied to millions of acres (Pilliod et al. 2017) has become one of the largest restoration efforts on earth. However, the restoration and especially aerial seeding efforts have had mixed results, and drought is one of the factors that is frequently considered to contribute to recovery failures (Hardegree et al. 2018) although formal tests of this hypothesis have not been done until the current project.

Wet-dry cycles underly the annual grass-fire cycle in sagebrush steppe (Pilliod et al. 2018) and dry periods that increase fire risks may persist in the first years after fire when post-fire rehabilitation interventions occur (DOI Emergency Stabilization and Rehabilitation program). In fact, until recently, nearly all of the many post-fire seedings were required to be completed in the first year after fire and any monitoring completed within three years. It has since been recognized that the challenges of restoration sagebrush and related perennials in light of drought would require an adaptive management strategy that 1) involved meaningful measurements of outcomes and use of the findings in subsequent management actions, and 2) allowed management treatments to be multi-phasic, applied in increments over years or be repeated if not initially successful (DOI Secretary Order 3336, 2015; and US Integrated Rangeland Fire Management Strategy 2016). Any restoration intervention in sagebrush steppe will face some probability of a water deficit sufficient to severely impact treatment success (Hardegree et al. 2018), and these policy changes enable managers to hedge their investments against drought and towards a greater likelihood of success. The hedging mechanisms include knowing whether recovery is occurring or not and ability to change the timing of treatments to better coincide with suitable moisture. However, there is a surprisingly little knowledge about "drought" effects in restoration, including for sagebrush steppe and other drylands. This knowledge gap limits our capacity to know with confidence that drought has caused restoration failures in the past and to predict when and where drought might affect current or future restoration investments, and how the drought effect can be mitigated. We addressed this information need by quantifying the level of water deficit and corresponding whether that has related to sagebrush stand recovery, or lack of recovery, retrospectively from hundreds of historic wildfires over the past ~40 years.

Our focus on "drought" in sagebrush steppe has some broader applicability because drought is generally considered to be a problem in the management of many plant communities and the habitat and ecosystem services they provide, worldwide. However, quantitative definitions of the level of water deficit that constitutes a substantive shift in ecosystem structure or function are needed and still do not exist for many natural resources in general. Water deficits are too commonly referred to as "droughts" when the outcomes are not clearly tied to a clearly defined and substantive loss of a natural resources (Slette et al. 2020). Accordingly, natural-resource managers and modelers do not yet have the information on ecosystem-hydrology thresholds needed to predict drought and mitigate its effects. Thus, our research questions, findings, and especially approach to quantifying drought have some generalizability to other ecosystem types beyond sagebrush.

To address the need for precise understanding of the level of water deficit that impacts sagebrush steppe habitat, we evaluated how post-fire recovery of sagebrush was related to historic weather and simulated soil moisture patterns across the western U.S. Sagebrush stands can be remarkably persistent, even over deep time (Beiswenger 1991), but the rapid transformation of mixed woody-herbaceous communities to grasslands occurs in a distinctly pulse-like pattern in sagebrush steppe, specifically in the failure of sagebrush to reestablish after wildfire (Miller et al. 2011). Thus, post-fire (re)establishment of sagebrush can be considered a point of sensitivity, and water deficits that impact it could thus cause ecosystem transformation. We performed intensive analysis of the relationship of sagebrush to weather and soil moisture, extensively over decades and across much of the western U.S. Our objective was to quantitatively define "ecological drought", in terms of the water deficit compounded by warmer temperatures that leads to type-conversion of perennial sagebrush stands to annual grasslands.

Organization and Approach:

Overview: Our assessment of sagebrush occurred across the western US and over hundreds of historic wildfires and sagebrush seedings, comprising millions of acres. We integrated newly released USGS maps of sagebrush cover available for most years from 1984 to current using the NLCD-BIT along with many hundreds of field plot estimations with reconstructed weather and simulations of soil moisture. The scope of the project was made possible by the coordination of the Southwest, Northwest, and North Central CASCs, which led to a broadening of the input and resources required for the extensive data gathering and quantitative analyses. The concept for this research was co-produced by the USGS science team through long-standing partnerships with the BLM, FWS, DOI Interior Burned Area Emergency Response team, state agencies, and the Interagency Sagebrush Seed team (state, industry, federal). This study directly addresses numerous priorities in the Integrated Rangeland Fire Management Strategy.

The team involved specializations in sagebrush ecophysiology, ecohydrology and statistics (PI M Germino and, funded support for co-PI D Barnard and then postdocs R O'Connor and A Simler-Williamson and PhD candidate C Applestein), soil water modeling (co-PI J Bradford, with funding for co-PI R Shriver and technician C Andrews), archives of post-fire treatments outcomes and the Land Treatment Exploration Tool (co-PI Pilliod, with funding for LTET programmers M Jeffries and L Schueck), and extensive mapping of historic vegetation change (co-PI Homer). Key weather and climate guidance or data came from S Hardegree and J Abatzoglou. Critical management involvement came from the national program to field office level in the BLM for data gathering, and from many post-fire rehabilitation specialists including Kevin Gunnell (Utah Department of Wildland Resources), BLM specialists such as C Fritz, T Warren, S Urhig, and many other managers and scientists in the Interagency Sagebrush Seed Working Group. The USGS EROS team provided in kind support on early data releases and interpretation of the NLCD data set, including M Rigge. We discovered greater opportunities to expand the drought-related information proposed for the Land Treatment Exploration Tool (https://www.usgs.gov/centers/fresc/science/land-treatment-exploration-tool?qt-science_center_objects=0#qt-science_center_objects), and co-PI J Bradford along with his technician C Andrews procured additional funding from the USGS Center for Data Integration (CDI) to provide wall-to-wall soil water simulation data derived from published models into the drought module tool that is the primary extension product of this CASC project.

Key steps and approaches: This project was multiphasic, with our core research questions requiring precursor tasks or studies to answer methodological questions. Preparatory steps included (1) virtual workshops with managers and specialists to develop *a priori* definitions for different forms of drought, (2) determining the optimal time frames and lag effects to consider in relating antecedent weather to ecological events such as sagebrush presence (a step we did not appreciate *a priori* to be necessary; Applestein et al. 2021), (3) computations to simulate soil water availability, assessing the reliability of the NLCD remote data that first became available to us in complete form from co-PI C. Homer's team in late spring 2020 (Applestein and Germino 2021), and (4) extensive computation required to create the maps of drought indices (overcoming problems in underlying weather-data series), and (5) identification of clusters of similar pixels within burned areas and computation of satellite data for the NLCD analysis).

The workshops consisted of several teleconferences and a webinar held in fall of 2018 in which we (1) re-introduced the concept, approach, and objective of the project, (2) discussed what ecological drought means and how it might be quantified for our application, usefulness of existing drought planning tools, and unmet manager's needs, (3) refined what can be produced

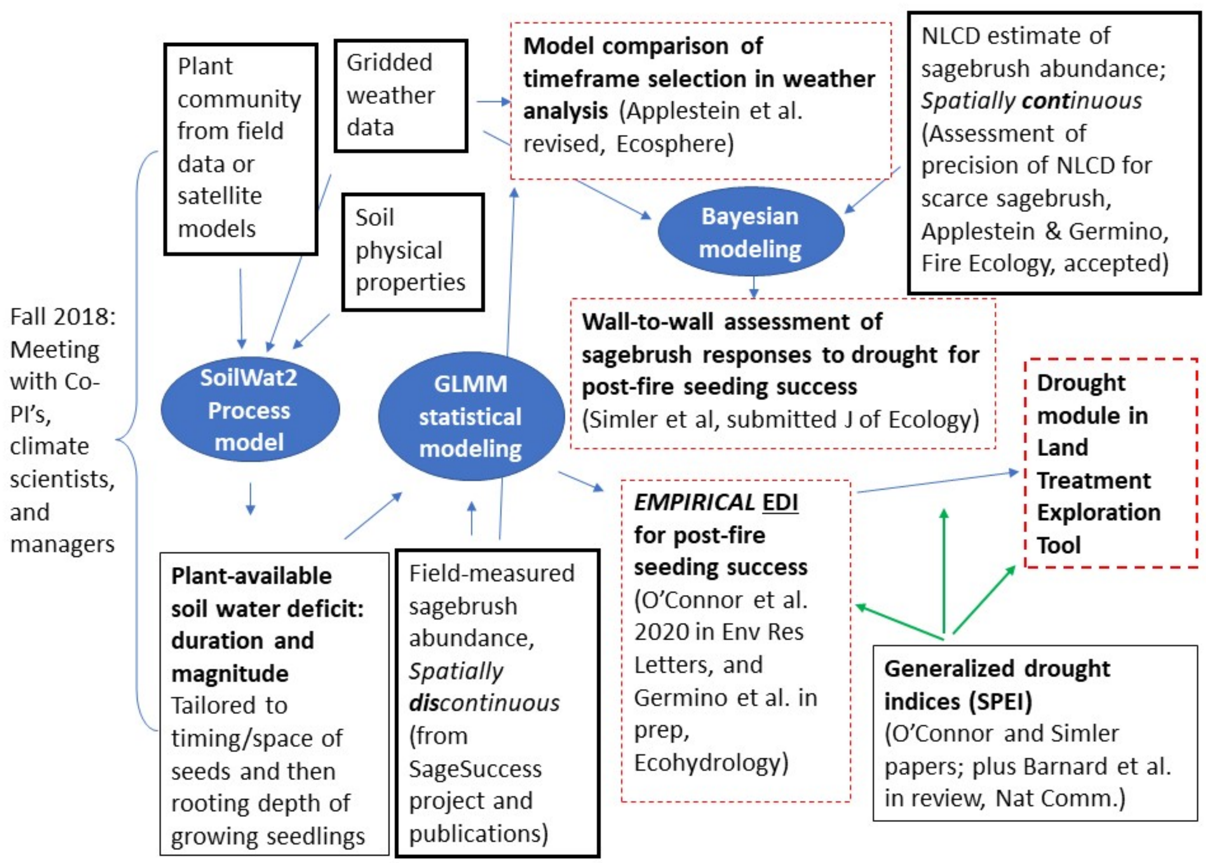


Figure 1. Schematic linking data inputs, processing, and outputs. EDI refers to Ecological Drought Index, SPEI is the Standardized Precipitation-Evaporation Index, GLMM is Generalized Linear Mixed Model, and NLCD is National Land Cover Database.

from the current project to fill information and tool needs, and (4) created an outline for *bridging scientific and management perspectives on challenges and opportunities for addressing ecological drought in post-fire restoration*. This outline helped focus momentum forward with our large team. The PI's also presented preliminary findings and obtained key feedback from managers at two national meetings, the National Emergency Stabilization and Rehabilitation meeting and the national Burned Area Emergency Response team lead meeting, as well as the regional Great Basin Fire Exchange via a webinar – all during the first year of the project.

Methods for determining sagebrush cover in the field are described in papers that preceded our project and which used the same field dataset on sagebrush from the USGS/BLM joint SageSuccess project and procedures for simulating soil water using the SoilWat2 model (Shriver et al. 2018, Barnard et al. 2019). Our use of general linear models to relate the field-estimates of sagebrush cover to soil moisture to quantify ecological drought are described in O'Connor et al. (2020).

Project Results, Analysis and Findings:

Analysis and findings:

Our keystone science discovery was that, compared to field plots where sagebrush had not recovered, field plots that had sagebrush 3-40 years after post-fire seeding had greater soil-water availability in the year just following fire and seeding, when most sagebrush establish (O'Connor et al, 2020). "Ecological drought" in terms of stand failure for big sagebrush could be defined in hydrothermal accumulation terms, specifically as the number of wet-warm days occurring in the brief post-fire period when most germination and initial establishment of sagebrush occurs. Sites that had no sagebrush years after fire had a mere 7 fewer days on average with mean temperature above freezing and soil water in the plant-available range (greater than -2.5 MPa) in the top 5 cm of soil (near surface) during the critical post-fire germination period (March of the year after fires). Model validation revealed that this ecological drought estimate was applicable across much of the sagebrush domain in the western US (O'Connor et al, 2020). Hereafter, we refer to this outcome as the CASC Ecological Drought index (EDI) for post-fire sagebrush recovery. We then asked whether the water deficits could also be detectable in deeper soil horizons over more years, specifically the first few years spanning the time of sagebrush establishment to reproductive maturity, when a recovering stand is capable of self-seeding the site. The findings of this expanded research will be important because restoration scientists and managers tend to focus on initial plant emergence and establishment without consideration of the factors affecting stand persistence.

In the gridded analyses, we asked whether the drought effects evident in field plots were detectable at much coarser scales but with unlimited spatial extent in the NLCD data (Simler-Williamson et al. 2020). A preparatory assessment on the NLCD "back-in-time" data (released

June 2020) revealed to us that the NLCD data represent sagebrush stands adequately when sagebrush cover is relatively high, but have considerable mismatch from field data when sagebrush is scarce - which is the case in the years following fire (Applestein et al. 2021). Hence, we developed a Bayesian statistical model for sagebrush responses to weather that could account for the error in remotely sensed estimates of sagebrush (Simler-Williamson et al. in review). The resulting analysis provides insight on how inclusion of weather can affect the accuracy of very broadscale models of post-fire sagebrush recovery, and whether the variations are consistent with drought effects.

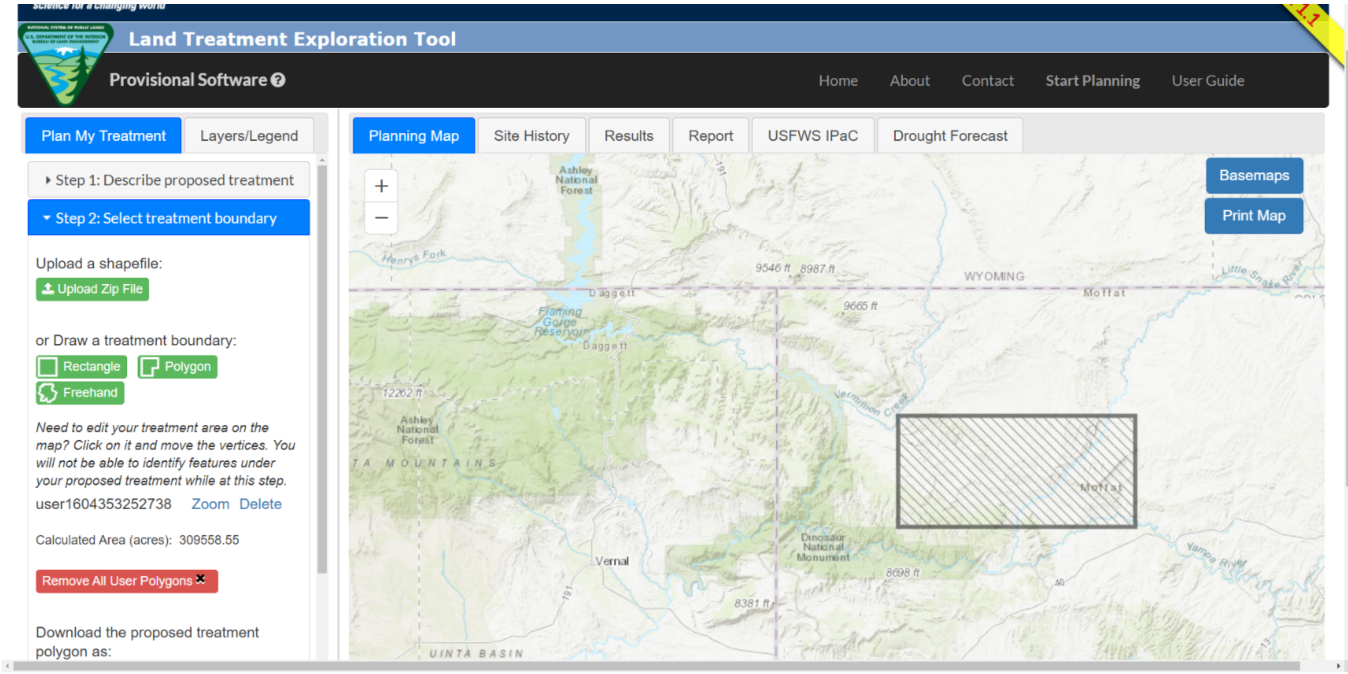
The relationships of post-fire sagebrush recovery measured in the field or with remote sensing to either post-fire precipitation or air temperature, or soil temperature and moisture, are not matched by drought indices (O'Connor et al. 2020). Specifically, the best-available drought indices that are standardized to allow flexible scaling to relevant time frames and also consider both precipitation inputs as well as temperature and evaporative demand (potential evapotranspiration) - such as SPEI (Standardized Precipitation Evaporation Index) - were unrelated to post-fire sagebrush recoveries (O'Connor et al. 2020). This lack of explanatory or predictive power of SPEI for sagebrush recovery appears due to SPEI's lack of relationship to variations in soil-water that result from key seasonal hydrologic processes for sagebrush, specifically winter recharge of deep soil water needed for established and reproducing plants or the shallow-soil wetting that is key for seedling emergence after fire (Barnard et al.in review).

Key result: Creation of a drought module for the Land Treatment Exploration Tool

The capstone outcome of our efforts was a translation of our findings into tools for managers, which was integrated as a new drought module into the existing Land Treatment Exploration Tool (LTET) website that was previously developed by the USGS team led by D. Pilliod and J. Welty, which has been provisionally released by the USGS Information Product System and has an anticipated full release date of May 2021. The LTET has been pilot-tested by land managers in the U.S. Department of Interior and other landowners and restorationists in the planning of fire rehabilitation efforts including sagebrush seeding. As part of this process, managers receiving funds for seedings or other post-fire treatments are required to use the LTET to obtain relevant spatial information on soils, climate, weather, outcomes of previous restoration projects that are germane to the site of interest, and now drought status.

The LTET has now incorporated a drought tool within the tab for site history (Figure 2), in which we now show the SPEI values for the site over various lengths of historical time for areas of interest. An additional tab illustrates drought forecasting with a drop-down menu that includes forecasted moisture and temperature and its relationships to seed and seeding success (Figure 3-5). As shown in Figure 5, sagebrush establishment can be predicted with tools that estimate the likelihood of sagebrush establishment based on the CASC EDI for sagebrush recovery and soil-water availability, as it is affected by both weather and soil physical properties (O'Connor et al. 2020). We also included tools based on the findings from previous models that predict establishment success from soil-water content, which relates readily to site temperature and precipitation (Shriver et al. 2018; Figure 5). The CASC EDI model differs from the previous models in that it is parameterized with simulations of the actual conditions affecting establishment events, whereas the Shriver et al. (2018) model informs the user of how sites that differ in long-term moisture, specifically snow-water equivalents, differ in likelihood of establishment.

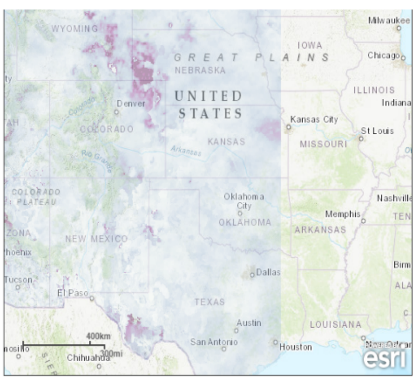
The tool will enable managers interested in a specific sagebrush post-fire seeding area to ask: 1) aside from the mean annual temperature and precipitation, how prone to drought is the area? 2) what has been the ecological drought condition of the water year prior to the fire? and 3) what is the forecasted ecological drought condition for the current water year? Information addressing these points is provided in mapped and table form in a report created by the LTET for the user's area of interest.



Historical Drought:

Below, we provide a map of one of the most useful drought indices for translating meteorological drought into an index that is able to represent moisture in ecosystems, known as SPEI, the Standardized Precipitation Drought Index (Vicente Serrano et al. 2010), which is useful in assessing how "drought" prone site(s) of interest are based on long-term climate and tendency for the site to have annual deviations from climate. Several drought indices are available, but SPEI has become more widely used in settings such as the western US because the index incorporates temperature through basic calculation of precipitation minus potential evapotranspiration, and furthermore has been standardized using more complex calculations to make the index scalable for different applications (from the site to continent). SPEI values are zero in the long term, unless directional change in moisture availability are occurring. SPEI typically range from approximately +2 to -2 for substantive wet and dry periods, respectively, and up to +4 and -4 for extreme wet or dry periods.

For the most recent SPEI Drought Map, see the SPEI Global Drought Monitor .



SPEI 2001-2014 Standard Deviation

0 50 100

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Enter any notes about the drought history that you would like included in the report:

Figure 2. An introductory page of the Land Treatment Exploration Tool where the user selects an area of interest (top box) and content added into the "site history" tab for this CASC project, including SPEI content and drought tool links nested within the tab (bottom). The tool will have a public-facing URL when the USGS review is approved.

Links for additional drought information:

- U.S Drought Portal National Oceanic and Atmospheric Administration's (NOAA) National Integrated Drought Information System (NIDIS).
- Climate.gov's weekly drought map The U.S. Drought Monitor (USDM) map shows the location and intensity of areas currently experiencing abnormal dryness or drought across the United States.
- United States Drought Monitor The U.S. Drought Monitor shows parts of the U.S. that are in drought.
- Western Regional Climate Center The Western Regional Climate Center delivers climate services at national, regional and state levels.
- Drought Index Portal A tool to display, compare, and extract time series for various indicators of drought in the Contiguous United States.
- SPEI Global Drought Monitor SPEI Drought indices for historic or contemporary conditions for a particular location.
- National Weather Service Climate Predictions Standard weather forecas

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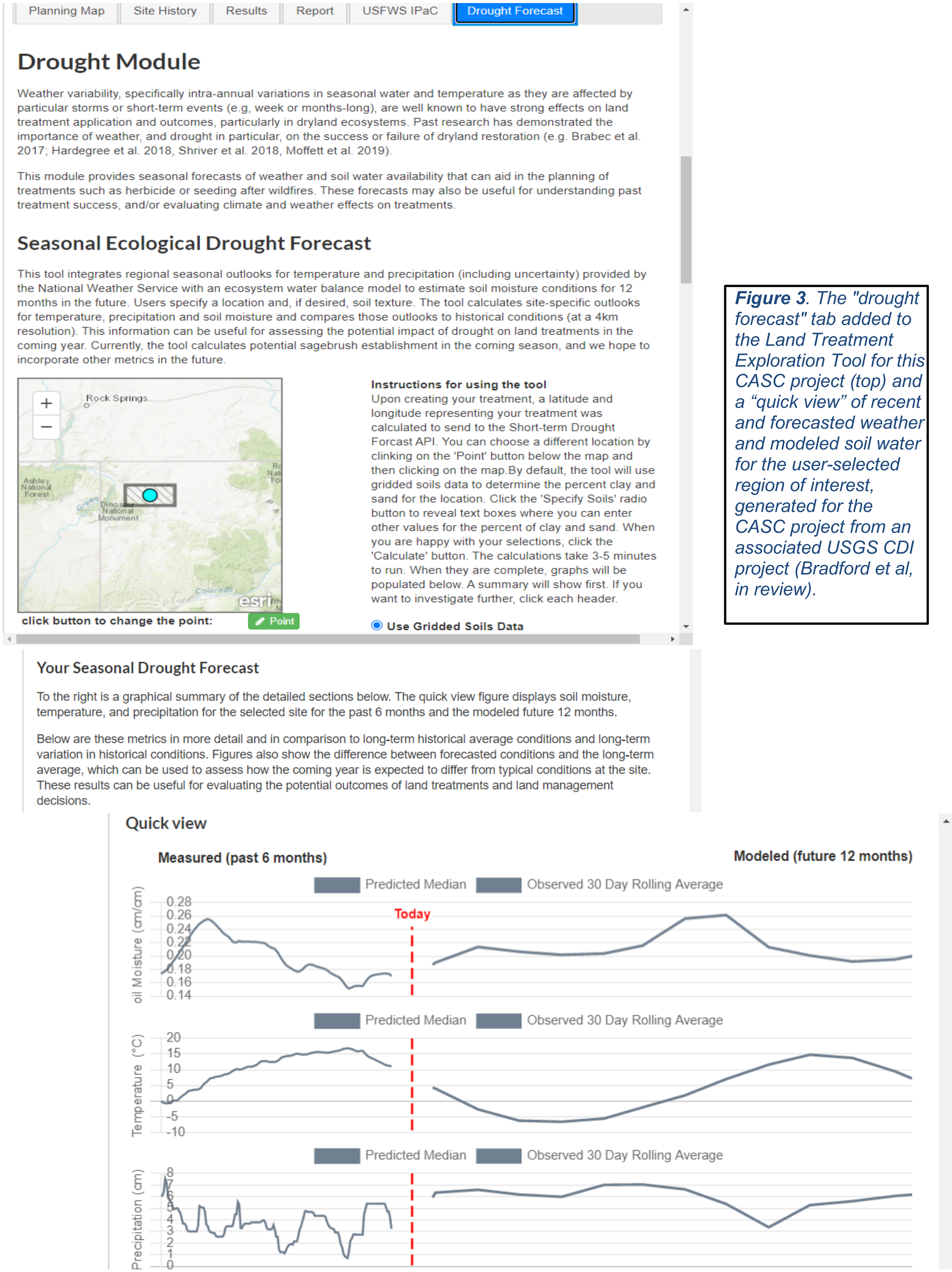


Planning Map | Site History | Results | Report | USFWS IPaC | Drought Forecast

Drought Module

Weather variability, specifically intra-annual variations in seasonal water and temperature as they are affected by particular storms or short-term events (e.g, week or months-long), are well known to have strong effects on land treatment application and outcomes, particularly in dryland ecosystems. Past research has demonstrated the importance of weather, and drought in particular, on the success or failure of dryland restoration (e.g. Brabec et al. 2017; Hardegree et al. 2018, Shriver et al. 2018, Moffett et al. 2019).

This module provides seasonal forecasts of weather and soil water availability that can aid in the planning of treatments such as herbicide or seeding after wildfires. These forecasts may also be useful for understanding past treatment success, and/or evaluating climate and weather effects on treatments.

Seasonal Ecological Drought Forecast

This tool integrates regional seasonal outlooks for temperature and precipitation (including uncertainty) provided by the National Weather Service with an ecosystem water balance model to estimate soil moisture conditions for 12 months in the future. Users specify a location and, if desired, soil texture. The tool calculates site-specific outlooks for temperature, precipitation and soil moisture and compares those outlooks to historical conditions (at a 4km resolution). This information can be useful for assessing the potential impact of drought on land treatments in the coming year. Currently, the tool calculates potential sagebrush establishment in the coming season, and we hope to incorporate other metrics in the future.

click button to change the point: Point

Instructions for using the tool
Upon creating your treatment, a latitude and longitude representing your treatment was calculated to send to the Short-term Drought Forcast API. You can choose a different location by clinking on the 'Point' button below the map and then clicking on the map.By default, the tool will use gridded soils data to determine the percent clay and sand for the location. Click the 'Specify Soils' radio button to reveal text boxes where you can enter other values for the percent of clay and sand. When you are happy with your selections, click the 'Calculate' button. The calculations take 3-5 minutes to run. When they are complete, graphs will be populated below. A summary will show first. If you want to investigate further, click each header.

Use Gridded Soils Data

Your Seasonal Drought Forecast

To the right is a graphical summary of the detailed sections below. The quick view figure displays soil moisture, temperature, and precipitation for the selected site for the past 6 months and the modeled future 12 months.

Below are these metrics in more detail and in comparison to long-term historical average conditions and long-term variation in historical conditions. Figures also show the difference between forecasted conditions and the long-term average, which can be used to assess how the coming year is expected to differ from typical conditions at the site. These results can be useful for evaluating the potential outcomes of land treatments and land management decisions.

Quick view

***Figure 3**. The "drought forecast" tab added to the Land Treatment Exploration Tool for this CASC project (top) and a “quick view” of recent and forecasted weather and modeled soil water for the user-selected region of interest, generated for the CASC project from an associated USGS CDI project (Bradford et al, in review).*

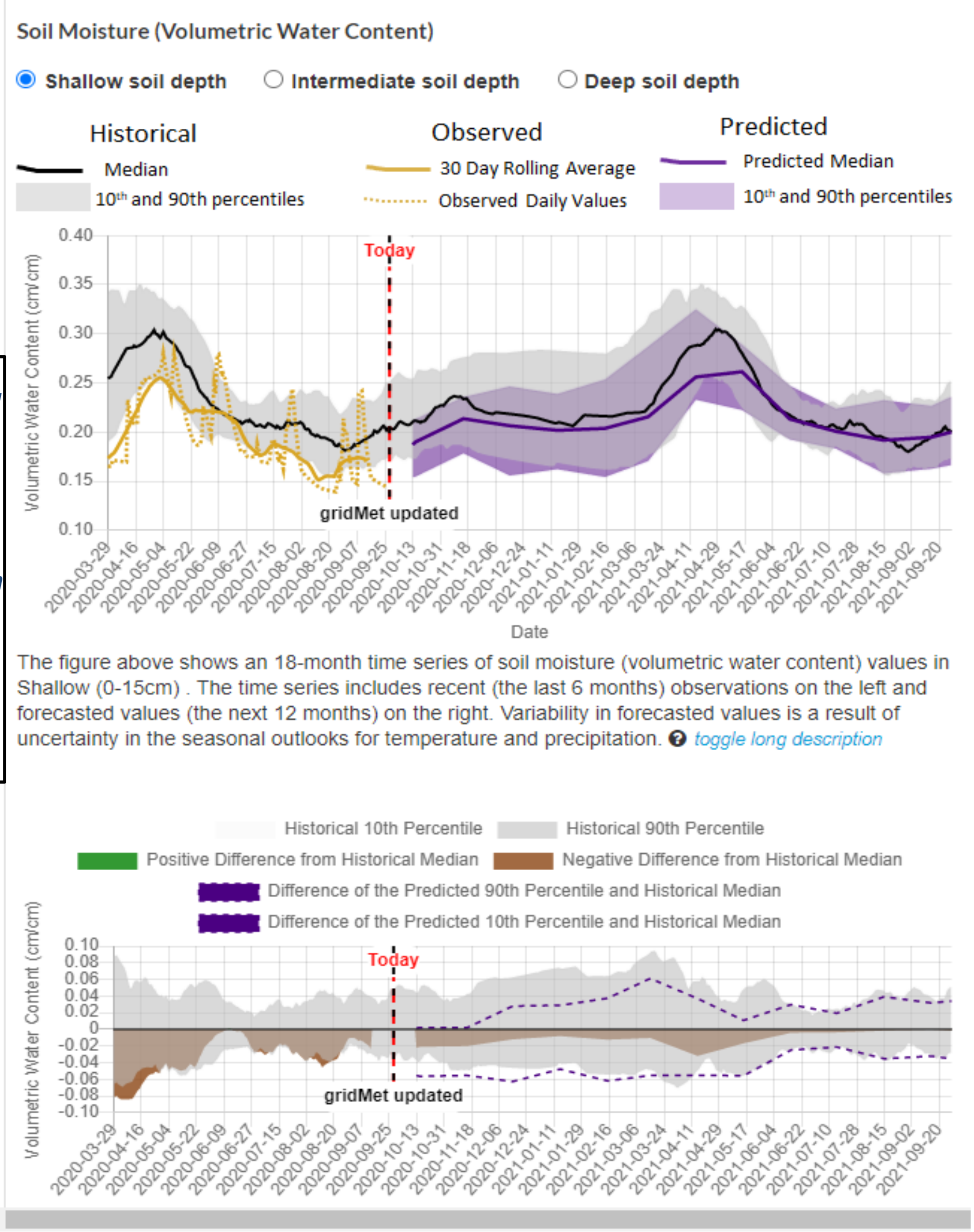
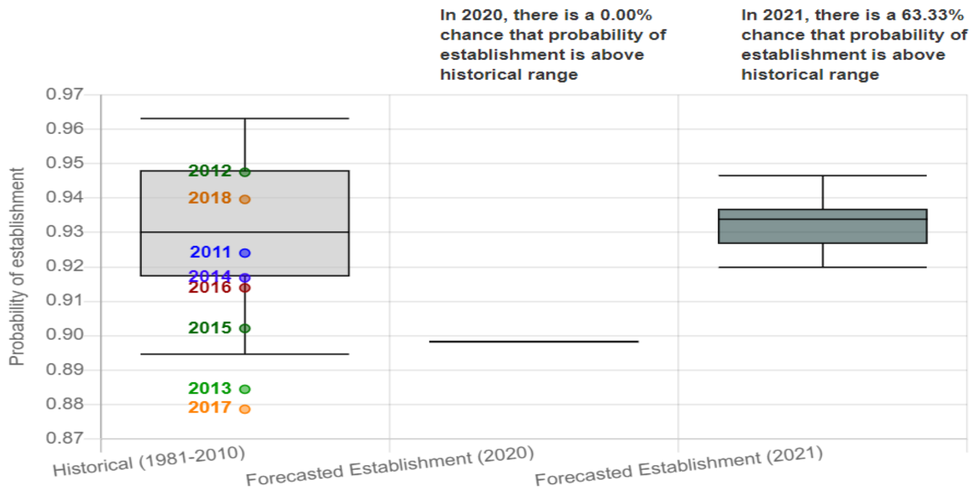


Figure 4. *Detailed soil moisture and associated temperature and precipitation data provided for the user-selected region of interest with the "drought forecast" tab added to the Land Treatment Exploration Tool, including retrospective long-term climate, current conditions, and future forecasted conditions generated for the CASC project from an associated USGS CDI project (Bradfords et al, in review).*

Study 1 (Shriver et al. 2018)

This study emphasized burned areas across the Great Basin, focusing on the relationship of successful seedings to soil moisture and temperature during the years following restoration.

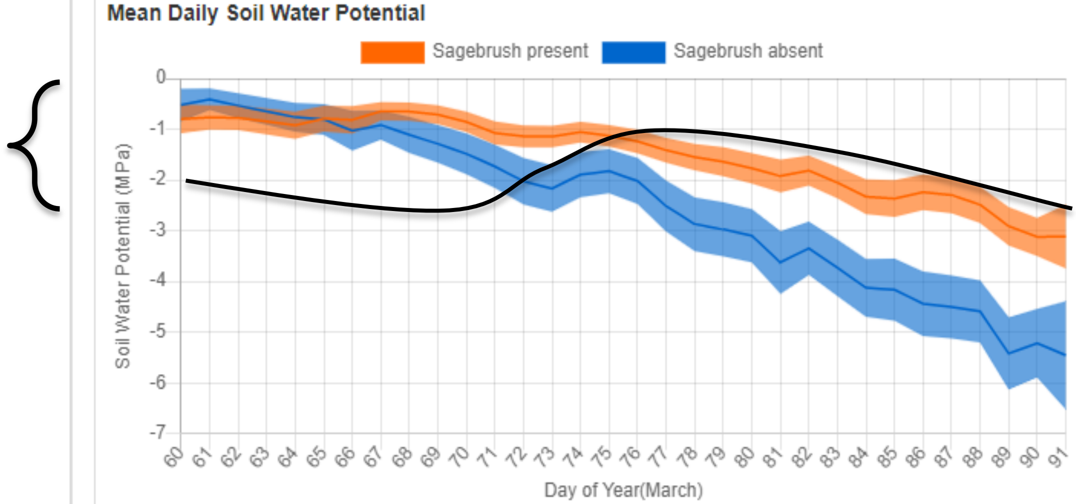


The boxplot on the left represent the median and the range of sagebrush establishment in the climatic normal period (1981 - 2011). Individual points of probability of success in more recent years are marked. The center and right-most boxplot are predictions for probability of success for 2020 and 2021. The boxplots represent the range across potential realizations of the future.

Study 2 (O'Connor et al. 2020)

This study focused on post wildfire treatments that were seeded with sagebrush. They evaluated the combination of spatial variation in climate (like the Shriver et al. study) but also the time-varying effects of weather, focusing on the top soil layer (0-5 cm) and calendar dates when sagebrush germinates and initial seedling survival occurs (March). These figures allow for the comparison between the user selected location and sites where sagebrush was or was not present.

Mean Daily Soil Water Potential



Mean daily soil temperature (top layer of soil/0-5cm only) across all sites used in O'Connor et al. 2020 study, where sagebrush was present (orange) and absent (blue), with a 95% confidence interval in shaded band. The average historical conditions for the selected site and 95% confidence interval are shown in black. If the black and orange lines are similar, then the selected site has a similar soil temperature in March as did sites where sagebrush was present post wildfire seeding.

▸ Potential Natural Sagebrush Seedling Survival

▸ References

▸ Methods

***Figure 5**. Tools added for this CASC project to the Land Treatment Exploration Tool to help predict sagebrush establishment potential after post-fire seedings for the user-selected region of interest in the "drought forecast" tab's "Sagebrush Seeding Success" drop-down menu, using the microclimate estimated in Figure 4. The top graph is predictions based on the SageSuccess project data and simulations of soil-water content and associated weather (Shriver et al. 2018) and the bottom panel shows how forecasted soil water (and temperature, not shown here) in the black line relates to soil-water availability where sagebrush had been detected (orange) or not (blue) in hundreds of previous burn areas, during the critical days of spring when sagebrush establish (O'Connor et al. 2020). The black bracket ({) shows the range of soil water that is available to sagebrush seedlings (0 to a dry -2.5 MPa).*

Conclusions:

The body of our completed work indicates that quantitative definitions of "ecological drought", in terms of the actual water deficit and related temperature conditions that trigger major habitat or land cover changes, are feasible to determine, even across broad spatial and temporal scales. This can be accomplished by first considering the demographic points of sensitivity in the populations of interest as they vary with key landscape drivers, which in the case of sagebrush is seedling establishment prior to grass recovery after wildfires. Next, compiling information on population outcomes across a sufficient spatial and temporal domain provides the response variable to which weather and soil moisture can be compared. In the case of sagebrush, field-estimates of canopy cover were necessary, but some supporting inference on favorable and unfavorable weather were also possible with remotely sensed data for "wall-to-wall" estimations of cover. Translating historical weather data into the soil-moisture availability and temperature that is actually experienced by plants as a function of their phenology and form (e.g., rooting depth) is just recently much more feasible with the SoilWat2 model simulation access that is now part of the preliminary LTET Drought Module that was produced in part from this project. All combined, these tools and approaches enable users to identify the weather thresholds, specifically drought conditions, that may cause major vegetation shifts and accompanying changes in habitat and ecosystem services. These advances are significant, because until recently, the information needed to evaluate threshold responses of plant communities to weather was typically possible for thermal but not hydrological variables, owing to the ease of statistically describing temperature but not soil-moisture extremes for broad scale analyses.

Through the involvement of land managers, we have learned that identifications of thresholds are key for management, such as for establishing criteria for seeding success or planning seeding treatments. Results suggest that future research guiding management under risk of drought consider from our example that quantification of ecological drought it feasible. For managers of sagebrush steppe and similar plant-community types, water deficits are a regularly occurring phenomenon that coincide with the wet-dry cycles that produce wildfire fuels, ignitions (lightning storms), and the hot dry conditions that create fire. Sagebrush steppe is a water-limited community type, and the weather and water deficits that result in fire tend to persist during the first year(s) following fire, which is when the majority of seedings have occurred. Moving forward, our research reveals that water deficits substantial enough to be called "ecological drought" because they appear to cause failure of sagebrush to recover after fire (even when seeded) have occurred more often than not. Management strategies for hedging seeding investments against drought can include: 1) using the LTET drought tool, 2) potentially reducing investment when drought appears imminent during the critical post-fire establishment phase, and 3) distributing the investment across multiple years to increase the odds of obtaining the weather and soil moisture conditions identified here as promoting sagebrush establishment, though this may entail use of herbicides and other management tools to decrease herb abundances that become appreciable by the second and later years after fire.

This CASC team accomplishment is significant, considering that sagebrush is the defining canopy cover type for sagebrush steppe habitats, which have declined by nearly 50% in recent decade and are otherwise one of the most widespread plant cover types in North America. The declines contribute to critical problems for conservation of dependent wildlife such as the Greater Sage Grouse. The science and translational ecology produced here are actionable in several ways: providing a tool to help managers decide where and when to invest seeding, and also for helping explain why past seedings may have succeeded or not. These are important for helping managers appropriately set expectations for seeding success and metrics for it.

Outreach and Products:

Publications:

Applestein C, Germino MJ. 2021. Detection of dominant shrub recovery using vegetation maps derived from 30-m satellite imagery: when does the signal emerge and how does it compare with field-based data on historic wildfires in sagebrush steppe? Fire Ecology. 17(1-11)

Applestein CA, Caughlin T, Germino MJ. 2021. Weather affects post-fire recovery of sagebrush-steppe communities and model transferability among sites, Ecosphere. *12*(4), p.e03446

Barnard DM, Germino MJ, Bradford JB, O'Connor RC, Andrews CM, Shriver RK. In Review. The limits of meteorological drought metrics for quantifying ecologically-relevant drought in drylands. Nature Communications.

O'Connor, R.C., Germino, M.J., Barnard,D.M., Andrews, C.M., Bradford, J.B., Pilliod, D.S., Arkle, R, Shriver, R.K. (2020). Small-scale water deficits after wildfires create long-lasting ecological impacts. Environmental Research Letters, 15(4)

Simler-Williamson AB, Applestein C, Germino MJ. In Review. Post-fire weather predicts dryland restoration outcomes across a wide spatial and temporal extent. J Applied Ecology.

In Prep:

CASC Ecological Drought team. Relationships of restoration success and soil-water availability among phenological and developmental stages broadens understanding of demographic responses to ecological drought. Ecohydrology

Germino MJ et al. Bridging scientific and management perspectives on challenges and opportunities for addressing ecological drought in post-fire restoration. Rangeland Ecology and Management

Field tours and discussions:

Germino MJ. 2018 Field tour of Soda Wildfire site and discussion of factors affecting sagebrush recovery and drought study plans. CASC Program staff (30 participants), Aug 17

Germino MJ. 2018 Field tour of Soda Wildfire site and discussion of factors affecting sagebrush recovery and drought study plans. BLM staff (15 participants), Oct 3

Germino MJ. 2018. Factors affecting post-fire seeding success. Invited presentation followed by full day field tour of Soda Wildfire site, to Joint Fire Science Program's Great Basin Fire Science Exchange board, Oct 11

Germino MJ. 2019. Invited presentation followed by field presentation on post-fire sagebrush recovery including climate and drought effects, to Sage Grouse Initiative annual meeting (>200 participants, 3 coach buses), May 23

Invited presentations to interagency leadership or partnership meetings:

Germino MJ. 2018. Insights on Post-Fire Restoration; followed by panel session. SageCon annual meeting (Sagebrush Conservation Partnership), Ontario OR, Oct 25

Germino MJ. 2018. Post-fire restoration. Department of Interior, Burned Area Emergency Response National Leads Annual Meeting, National Interagency Fire Center, Boise, Feb 8

Germino MJ. 2019. Challenges and opportunities for science and management of burned sagebrush steppe. Webinar presentation to Idaho NSF EPSCoR leadership and science team, May 29

Germino MJ. 2020. Presentation and discussion (in person) on post-fire restoration with the DOI Assistant Secretary for Water and Science (Dr. Tim Petty), The Director of the USGS (Dr. J Reilly), and the Regional Executive for the USGS Pacific Northwest (Dr. Jill Rolland). USGS Idaho Water Science Center. Aug 25

Symposia:

Adaptive Management of Burned Rangelands: Challenges and Opportunities for Its Co-Production By Land-Agency Staff and Scientists. Symposium with presentations by CASC PIs Germino and Pilliod, along with BLM program managers K Prentice and L Van Riper, followed by panel. Society for Range Management Annual Meeting, Denver CO, February 2020.

Drought in semiarid rangelands: An international, cross-disciplinary look at how we know can know when water deficit matters. Virtual symposium presented February 18, 2021 to the Society for Range Management Annual Meeting. Speakers include two PIs from this CASC project presenting the research findings described in this report (Germino, Bradford), plus members of the climate tools advisory group who developed climate/drought tools we used (Abatzaglou on GridMet, Vicente-Serrano on SPEI), and two other ecologists to talk about ecological drought effects in other rangelands (A Knapp, Dust Bowl drought effects; W Bond, synthesis of rangeland responses to Africa's severe drought). The symposium was recorded and is available at the meeting website.
https://annualmeeting2021.rangelands.org/

Ecological drought and recovery of sagebrush after wildfire. Symposium 100% dedicated to this CASC project delivered virtually by six participants from the study, each presenting a different sub-topic from the project, Northwest Climate Meeting, April 7,2021. The symposium was recorded and is available at the meeting website.
https://www.nwclimateconference.org/program.html

Presentations at society meetings or invited lectures:

Germino MJ. 2018. Post-fire recovery, rehabilitation, and restoration in sagebrush steppe Bi-Annual Meeting National BAER Team, Reno NV

Germino MJ. 2018. Big Picture Considerations for Sagebrush Restoration. SageSuccess Webinar, Great Basin Fire Exchange.

Shriver RK, Andrews CM, Pilliod DS, Arkle RS, Welty JL, Germino MJ, Duniway MC, Pyke DA, Bradford JB. 2018 Environmental controls on restoration success of big sagebrush: Implications for adaptive management. Ecological Society of America Annual Meeting, New Orleans LA

Applestein C, Germino MJ, Caughlin T. 2018. Forecasting post-fire sagebrush recovery given interactions between sagebrush, exotic annual grasses, and perennial grasses under different climate scenarios. Pacific Northwest Annual Climate meeting, Boise ID

Applestein C, Germino MJ, Caughlin T. 2019. How post-fire weather variability affects the balance between sagebrush, exotic annual grasses, and perennial grasses, and what it means for climate change. NW CASC Annual Science Meeting, Portland OR

Germino MJ. 2019. Drought, plant adaptation, and restoration in sagebrush-steppe rangelands. Society for Range Management Annual Meeting, Minneapolis MN

Germino MJ. 2019. Restoring resistance and resilience in droughty ecosystems: landscape-scale evidence for the benefit of adaptive management. Society for Ecological Restoration 8th World Congress, Cape Town, South Africa

O'Connor R, Germino MJ, Andrews C, Arkle RS, Bradford J, Pilliod DS. 2020. What is ecological drought in rangelands? A quantitative definition from burned sagebrush steppe. Society for Range Management Annual Meeting, Denver CO

Cancelled presentations: Germino/ESA; GBSER session

Media and popular press:

Interview of MJ Germino by Keith Ridler of Associated Press, on science and management advances in sagebrush steppe rangelands; emphasis on adaptive management of burned areas in light of drought. Published inWashington Post, Bozeman Daily Chronicle, Idaho Statesman, Clinton Herald, Drovers.com, ncnnewsonline, khq radio/tv; 22 April 2019

Interview of MJ Germino on the grass-fire cycle and restoration of sagebrush steppe with Matt Podlesky for commonland podcast (broadcast on Radio Boise FM 89.9, widely available on spotify, itunes, etc.) https://commonland.wildlensinc.org/episode-nine-the-cheatgrass-fire-cycle, Spring 2020

Interview of C Applestein and MJ Germino, Podcast Episode 12 of "Fire Ecology Chats", entitled "Shrub Recovery in Sagebrush Steppe" on the Association for Fire Ecology website, April 16, 2021. https://fireecology.org/chats The interview acknowledges CASCs.

Communications with decision-makers, including their name and agency and the date(s) and frequency of your communications.

2018 (All PI's and project participants, November). Teleconferences and webinars for this CASC project, >15 land managers and agency specialists, to solicit input on direction and design of analyses and outreach.

2018 February (M Germino). Consulted on soil stability (including weather) assessment for Deer Park post-fire treatments on BLM Idaho Falls District (B. Dyer; ~20,000 acres).

2018 Summer (M Germino), Consulted with BLM Boise District (R. Bennet) on soil erosion risk assessments (including weather) for several planned, large-scale, post-fire treatments spanning >50,000 acres).

2018 (M Germino) Extended consultation on management and restoration response to the Sharps Wildfire (54,000 acres) to The Nature Conservancy and agency partners (T. O'Sullivan, BLM Shoshone Field Office).

2019 (M Germino) Assisted BLM National Office of Fire and Aviation (D. Havlina) in assessing BLM's Emergency Fire and Rehabilitation program, including developing surveys.

2019 February (M Germino). Responded to request from the Utah State program lead for ESR, (C. Addy) for guidance on anticipating wind erosion and how to monitor for it, including recommendations for treatment objective and monitoring protocols on the 150,000 acre Grouse Creek fire burned in 2018.

2018-2019 (18 months). Lead or contributing authors on chapters in the Sagebrush Conservation Strategy (forthcoming in 2020) organized by the Western Association for Fish and Wildlife Agencies (WAFWA), including the Restoration chapter (Germino et al, D. Pilliod contributing), and contributed to chapters titled Monitoring and Adaptive Management (D. Pilliod et al, M Germino contributing), Climate and Weather (M Germino and J Bradford contributing), among other contributions.

2020. Participation by MJ Germino (passive and intermittent contributor, due to time constraints) on CASC Deep Dive project on Climate and post-fire restoration (S. Hall).

2018-present (M. Germino). Founding participation in the Sagebrush Seed Working Group, and interagency team of ~20 members including the BLM National Seed Warehouse Program lead (T Roller), consisting of regular teleconferences and communicating science to managers.

2020. (All PIs and participants, including new agency staff who are end users, November 17). Final CASC project webinar to review all results and discuss implementation of findings and next steps.

Websites created (including data releases that are not imbedded into journal publications):

CASC drought module (IP address is 10.12.7.58), with a new "forecast" page, significant content added to the "site history" page, and narrative added to the guide: **http://app.dev-fresc.chs.usgs.gov/land-treatment-exploration-tool/**

Project website, created by the NC CASC staff:
https://www.sciencebase.gov/catalog/item/5b3160b9e4b040769c13ffca

Barnard, D.M., and Germino, M.J., 2020, Standardized Precipitation-Evapotranspiration Index for western United States, 2001-2014, derived from gridMET climate estimates: U.S. Geological Survey data release, https://doi.org/10.5066/P9MZKCWZ.

Other literature cited:

Barnard D, Germino MJ, et al. 2019. Soil characteristics are associated with the development of big sagebrush canopy structure after disturbance. Ecosphere 10.1002/ecs2.2780

Beiswenger, J.M., 1991. Late quaternary vegetational history of Grays Lake, Idaho. *Ecological Monographs*, *61*(2), pp.165-182.

Germino, M.J., Belnap, J., Stark, J.M., Allen, E.B. and Rau, B.M., 2016. Ecosystem impacts of exotic annual invaders in the genus Bromus. In Germino MJ, Chambers JC, Brown C, *Exotic brome-grasses in arid and semiarid ecosystems of the Western US* (pp. 61-95). Springer, Cham.

Hardegree, S.P., Abatzoglou, J.T., Brunson, M.W., Germino, M.J., Hegewisch, K.C., Moffet, C.A., Pilliod, D.S., Roundy, B.A., Boehm, A.R. and Meredith, G.R., 2018. Weather-centric rangeland revegetation planning. *Rangeland Ecology & Management*, *71*(1), pp.1-11.

Connelly, J.W., Knick, S.T., Braun, C.E., Baker, W.L., Beever, E.A., Christiansen, T., Doherty, K.E., Garton, E.O.,

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Pilliod, D.S., Welty, J.L. and Toevs, G.R., 2017. Seventy-five years of vegetation treatments on public rangelands in the Great Basin of North America. *Rangelands*, *39*(1), pp.1-9.

Shriver, R.K., Andrews, C.M., Pilliod, D.S., Arkle, R.S., Welty, J.L., Germino, M.J., Duniway, M.C., Pyke, D.A., and Bradford, J.B., 2018, Adapting management to a changing world--Warm temperatures, dry soil, and interannual variability limit restoration success of a dominant woody shrub in temperate drylands. *Global Change Biology* 24:4972-4982

Slette, I.J., Smith, M.D., Knapp, A.K., Vicente-Serrano, S.M., Camarero, J.J. and Beguería, S., 2020. Standardized metrics are key for assessing drought severity. *Global Change Biology*, *26*(2), pp.e1-e3.