Monitoring for Adaptive Management of Burned Sagebrush-Steppe Rangelands: Addressing Variability and Uncertainty on the 2015 Soda Megafire

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Monitoring for adaptive management of burned sagebrush-steppe rangelands: addressing variability and uncertainty on the 2015 Soda Megafire

By Matthew J. Germino, Peter Torma, Matthew R. Fisk, and Cara V. Applestein

On the Ground

- Use of adaptive management supported by robust monitoring is vital to solving severe rangeland problems, such as the exotic annual grass invasion and fire cycle in sagebrush-steppe rangelands.
- Uncertainty in post-fire plant-community composition and plant response to treatments poses a challenge to land management and research but can be addressed with a high density of observations over short time frames.
- The monitoring for adaptive management of the 2015 Soda Megafire area (113,000 Ha) sampled up to 2000 observation plots in each of five post-fire years, and provided important insights on challenges, solutions, and insights that can be applied to monitoring future burned areas.

Key words: Restoration, Co-production, Sampling effort, Annual grasses, Sagebrush, Bunchgrass.

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Background

Fires, exotic annual grasses, and restoration in sagebrush steppe

Using adaptive management in restoration or rehabilitation is particularly important where harsh and variable environmental conditions combine with the incomplete understanding of managed resources to create challenges in achieving management objectives (i.e., success). Monitoring and adaptive management are needed to address increasing wildfires in sagebrush-steppe rangelands.[1] Sagebrush steppe once occupied nearly 1,000,000 km^2 of Western N. America (nearly 250,000,000 acres) but has diminished to about half of its original extent due to the combination of fire and exotic annual grass (EAG) invasion by species including ventanata, medusahead, and especially cheatgrass (*Ventanata dubia*, *Taeniatherum caput-medusae*, and *Bromus tectorum,* respectively).[2] Over half of the original and contemporary area is administered by the US Department of Interior (DOI)'s Bureau of Land Management (BLM) for multiple land uses and sustained yield.

Historic grazing practices have led to decreases in deep-rooted bunchgrasses and invasion by EAGs.[3] EAGs increase the abundance and continuity of fine wildfire fuels and thereby also increase the frequency and size of fires beyond the adaptive capacity of native species such as sagebrush.[3] In turn, the resulting fires exacerbate EAG invasion and cause type conversion of native communities into fire-prone, ecologically degraded, EAG grasslands that have diminished stability and productivity.[4] The continued loss of sagebrush has led to severe management problems including threat of extinction of the greater sage-grouse (*Centrocercus urophasianus*) and conservation challenges for many other species.[5]

Post-fire management interventions have been applied throughout most sagebrush steppe for decades, including 1) passive restoration, which mainly entails deferment of livestock grazing (i.e., "rest"), or 2) active treatments, with herbicides to reduce exotic grass colonization or seedings to increase desirable perennials.[6] To illustrate the extent of treatments: more than 5,000 herbicide treatments covering nearly 2,500,000 ha (>6,000,000 acres); and >12,000 seeding treatments covering almost 6,000,000 ha (nearly 1,500,000 acres) are recorded in the US Geological Survey (USGS) Land Treatment Digital Library.[6] The herbicide treatments generally consist of the pre-emergent imazapic but also include some glyphosate and other herbicide types. Seedings consist mainly of aerial broadcast of grasses, forbs, and especially sagebrush (*Artemisia sp.*), or drill-seedings of perennial grasses and forbs. Examples of other treatments include soil treatments such as chaining to prepare seedbeds or incorporating aerial broadcast seeds into soils. While these treatments have led to successful outcomes in some settings, they have mixed or low success in their primary objectives of preventing loss of perennials.[7]

Rehabilitation and restoration projects are challenging in sagebrush steppe, owing to scarcity and temporal variability of precipitation, which ranges ~125-400 mm/y (~5-16 in/y) among sites but can varying > ±100 mm/y (~4 in/y) from year-to-year in a site. Water deficits are compounded by risks of freezing damage to seedings and competition from EAGs,[4,8] among other factors. Burn areas now occur in patches that can be 50,000 ha or even occasionally nearly 500,000 ha (~100,000-1,000,000 acres), and their remoteness frequently precludes inventory of their natural resources.[4] For example, the area burned in patches greater than 40,461 ha (100,000 acres; 66 fires totaling 11,210,116 ha or 127,700,801 acres) was 4.6-fold greater than the *sum* area burned by 4,000 fires up to 5,000 ha in size (12,355 acres; total area of 1,662,447 ha or 4,107,997 acres) in the records to November 10, 2021 for the Great Basin Geographic Coordination Center of the National Interagency Fire Center (http://data-nifc.opendata.arcgis.com). Data are scarce on the outcomes of these historic treatments across the large areas affected, and even scientific assessments of the treatments have typically been based on sparse sampling (e.g., few plots per burned area).[9] Thus, monitoring is needed to provide the information on how to improve post-fire management success and thereby increase desirable perennials and reduce EAGs in sagebrush steppe.

Policy change leading up to management of the Soda Megafire recovery

Population declines of the greater sage-grouse led to consideration of listing under the US Endangered Species Act in 2015, but the decision to not list it was associated in part with a US DOI commitment to address the underlying issues of fire and invasive EAGs (DOI Secretarial Order #3336).[10] The Secretarial Order was the foundation for identifying rangeland fire management as critical for protecting, conserving, and restoring sagebrush steppe ecosystems, and elevated concern and action on EAGs as a factor contributing to increased wildfire. The Secretarial Order[10] established a Rangeland Fire Task Force to develop the Integrated Rangeland Fire Management Strategy to address all aspects of fire management (IRFMS,[11] The Rangeland Fire Task Force, 2015). This included fire prevention, suppression, and restoration and the need to update DOI Department Policy "620 DM Chapter 7" on Post-Wildfire Recovery[12] (recommended in IRFMS Section 7(b)v, "Post-Fire Restoration").[11] The Secretarial Order[10] also motivated increased interdisciplinary and interagency involvement in the planning of rangeland post-fire management and coordinated restoration. A "Sagebrush Ecosystem Conservation: All Lands, All Hands" initiative was formed that promoted collaboration between management agencies, scientists, private landowners, industry, and others to sustain healthy sagebrush ecosystems across all boundaries. The Secretarial Order[10] was accompanied by change in management direction in the DOI post-fire recovery programs, specifically the Emergency Stabilization and Rehabilitation and Burned Area Response programs (ESR and BAR, respectively;[13] Bureau of Land Management, 2007). The revised 620 DM Chapter 7[12] focused on reducing the risk of resource damage and restoring landscape impacted by wildfire to promote long-term restoration and recovery objectives. This facilitated the need for robust effectiveness monitoring.

The ESR policy had previously allowed EAGs to be treated, but also restricted treatments to restoring vegetation to pre-fire conditions, to the extent they can be known over the vast and remote areas burned. Treatment objectives could focus on preventing degradation of perennial vegetation to invasive exotics, but not improving vegetation condition, leaving burned areas with high amounts of EAGs in many cases. This limitation was removed with the policy changes, allowing managers the option to improve the ratio of perennial:annual grasses. Moreover, ESR funds and treatments were historically allowed to be applied within 12 months after fire, thus providing only one dormant season (fall/winter). The 620 DM Chapter 7 revision[12] allowed implementing treatments until the end of the calendar year after the year of ignition (i.e., for a summer wildfire, this could provide ~1.5 years for treatments), with approval by the director of the BLM Office of Wildland Fire to allow ESR plans to be adjusted for unusual weather or other significant factors. Additionally, the revision of the Departmental manual emphasized the importance of connecting ESR and BAR actions to long-term site management, with BAR funding and projects likely extending longer (e.g., to 5-years post-fire).

All these ESR and BAR policy shifts increased opportunities to use adaptive management and thereby increased the need for effective monitoring. As Allen et al.[14] aptly stated, "Adaptive management is an approach to natural resource management that emphasizes learning through management based on the philosophy that knowledge is incomplete and much of what we think we know is actually wrong, but despite uncertainty managers and policy makers must act". The essential feature of adaptive management is the "treat-observe-learn-repeat" cycle in which ecosystem responses to initial intervention are used to update knowledge, and the information is then used to guide follow-on interventions.[1]

The Soda Megafire and management treatments following it

The first large wildfire to occur after release of the Secretarial Order[10] was the 2015 Soda Megafire (>~20k ha; 100,000 acres), which burned ~113,000 ha (~279,000 acres) of sagebrush steppe and a substantial amount of greater sage-grouse habitat in the Owhyee Mountains of the Northern

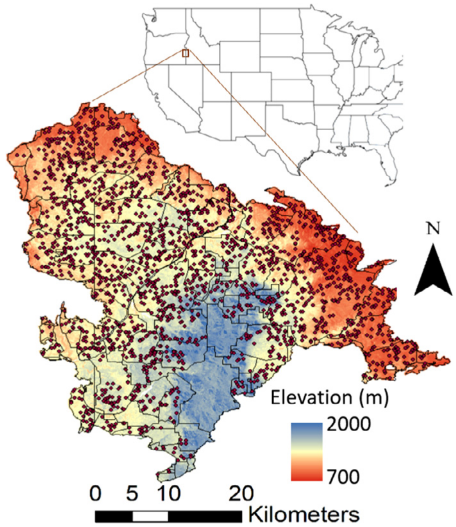

Figure 1. Field-data point (plot) locations where plots were measured on the Soda Megafire area. Variation in elevation is also shown in the fire area (lower map), and the location of the fire area in the United States is shown (upper map).

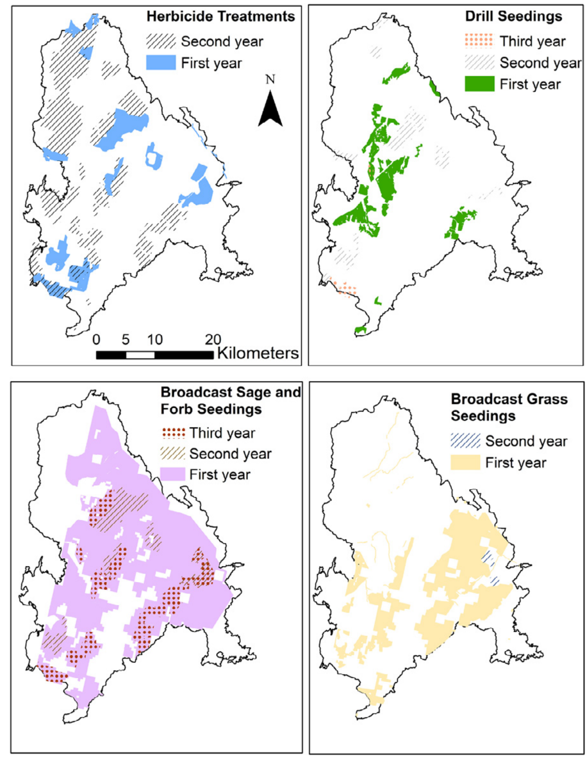

Figure 2. Spatial and temporal patterns of post-fire treatments applied to the Soda Megafire area, burned in summer 2015. "First year" refers to fall/winter of 2015/2016, "Second year" is fall/winter of 2016/2017, and "Third year" is fall/winter of 2017/2018.

Great Basin, along the Idaho/Oregon border. The fire moved rapidly from August 10-15, partially in view of the National Interagency Fire Center, the Cities of Boise, Idaho and Vale, Oregon, and the greater Treasure Valley metropolis of Idaho (Fig. 1). Approximately 72% of the burned area is managed by BLM which included 105 grazing units (allotments or pastures in Idaho and Oregon), 14% is managed by the State of Idaho, and 14% is owned by private landowners. The burn area was predominately Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) and had highly variable terrain soils, spanning from 700 m (2297 feet) elevation at the low-elevation ecotonal border with salt desert to the upper-elevation limit of Wyoming big sagebrush, near ~1800 m (5905 feet). The burn area thus encompassed a wide range of biophysical conditions thought to confer either low resistance to exotic annual grass invasion and low resilience to wildfire, to greater resistance and resilience at higher elevations.[15] Resistance and resilience in this context are enhanced by relatively cooler and wetter conditions, and by the abundance of resprouting and deep-rooted perennial grasses that can endure disturbances and water deficits and are better able to competitively preempt annual grasses than other plant types.[15] Aboveground biomass was nearly completely burned across the fire area, leaving a black/charred landscape with few patches of un- or partially burned vegetation. There was considerable concern about annual grass invasion into these burned sagebrush steppe habitats.

The federal, state, and local response to the Soda Megafire in Idaho and Oregon was more intensive than most previous post-fire management responses, and all elements of the treat-observe-learn-repeat cycle of adaptive management were used. The thoroughness of combustion over a large area combined with proximity or relation to Boise, NIFC, and the Secretarial Order all appeared help motivate the intensive adaptive management response. The project has accordingly become a national focus for understanding management of burned sagebrush steppe, in terms of national and regional level investment and attention. Examples of attention include multiple visits from the Secretary of the Department of Interior and directors of the BLM along with over 600 visitors from many federal and state offices observing the outcomes in dozens of field trips from 2016-2021, and presentations to many other people in the USA and abroad.

Management responses after the Soda Megafire were relatively more intensive and complex compared to post-fire interventions made after previous wildfires, due to size of the Soda Megafire and number of resources effected. The treatments included 1) temporary removal of wild horses, 2) deferment of livestock grazing, initially planned for either two growing seasons or until management objectives for recovery were met, and 3) herbicide and/or seeding treatments applied to many large polygons (Fig. 2). Other treatments not targeted by the monitoring described here included 4) hazardous material site assessment and clean-up, 5) road improvements, 6) fence repair, and 7) repairing damage to recreational trails.

The vegetation treatments included 1) aerial-broadcast seeding of sagebrush combined with three common forb species (small burnet, yarrow, and alfalfa; *Sanguisoriba minor* Scop., *Achillea millefolium* L., *Medicado sativa* L.) from helicopters in late fall and winter 2015/2016, with repeat seedings applied in subsequent years on small areas, 2) drill or aerial-broadcast seeding of grasses, 3) spraying with the pre-emergent herbicide imazapic (Fig. 2), 4) smaller scale and localized seedings of other shrubs and high-diversity mixes of forbs, and 5) ~1 M plantings of sagebrush (mean density of 44,733±12,916 seedlings per 5 ha, and 5 ha [12.3 acres] was the mean planting unit area).[16] Seeded perennial grass species included cultivars of bluebunch, Siberian, crested, Snake River, and thickspike wheatgrasses, squirreltail, Great-Basin Wildrye, Sherman big bluegrass, and Idaho fescue [*Pseudoregneria spicata* (Pursh) A. Love, *Agropyron* fragile (Roth) Candargy, *A. cristatum* L. Gaertn., *Elymus wawaiensis* J. Carlson & Barkworth, *E. lanceolatum* (Scribn. & J.G. Sm.) Gould, and *E. elymoides* (Raf.) Swezey; *Leymus cinereus* (Scribn. & Merr.) A. Love, *Poa secunda* Presl = *P. ampla,* and *Festuca idahoensis* Elmer, respectively]. Smaller areas of bitterbrush (*Purshia tridentata* (Pursh)DC) or low sagebrush (*A. arbuscula* Nutt.) or a diverse seed mix of native forbs preferred by greater sage-grouse were also applied.

The overlay of treatment types, years of treatment application, and grazing units with unique grazing plans created a complex mosaic of many areas requiring separate evaluation and decision making. This management complexity was compounded by the additional complexity created by variation in elevation, topography, soils, pre-fire vegetation condition, and other factors. Thus, a robust monitoring effort was needed to support adaptive management and evaluate treatment success.

The structure of sampling and setting objectives

The complexity of treatments required about 10 different objectives, each tailored to a specific vegetation or treatment type, which required a correspondingly sizable list of measurement variables and techniques. The science available to guide development of the objectives was and still is only partially complete due to gaps in published research, making some objectives hard to determine. A working group, referred to as the Soda Partners group (hereafter, "Partners"), consisting of many federal, state, and non-governmental agencies and their staff met frequently during the project and provided key input, discussion, and consensus on objectives and interpretation of vegetation responses. The Partners' vision for the burned area was to sustain or increase resistance and resilience, such that the landscape would not require intensive treatment intervention after subsequent fires. USGS and BLM led the details of the sampling plan, sampling procedures, and general logistics for the sampling. BLM delegated the actual sampling, data processing, statistics, and their development to the USGS. Objectives for the various treatments were based on quantitative thresholds, and were specific to different response variables, plant species or functional groups, and treatment types. The BLM and Partners needed the objectives and monitoring for them to be applied equivalently across the many pastures and other management boundaries including Oregon.

The objectives for perennial grasses were intended to ensure they had adequate abundance resulting from multiple individuals of substantial size, and the stands had sufficient reproduction to ensure self-replacement. For drill or aerial broadcast seedings of perennial grasses, treatment objectives were that perennial grasses had average foliar cover ≥ 20%, average density of ≥ 3 plants/m^2, and median basal diameter ≥ 7.62 cm (3 inches). The 20% cover threshold was obtained from studies done at local scales,[17] across the Great Basin,[18] or management guidance documents.[19] The density thresholds were from Evans and Young's[20] local-scale study, and basal diameter thresholds were derived from expert opinion. The sampling omitted the native bunchgrass Sandberg bluegrass, because this species was perceived by the land managers as less likely to outcompete EAGs compared to deep-rooted perennial grasses. As a sidenote, Sandberg bluegrass may have a soil-water use and phenology that more closely matches EAGs, especially cheatgrass.[21] These traits cause its growth and survival to be more sensitive to weather compared to deeper-rooted perennials that are more likely to endure and resume growth when drought ends. The role of Sandberg's bluegrass in resistance and resilience clearly requires more evaluation.

Additional variables for objectives included seed production, abundance of roots in terms of root depth and lateral spread, and seasonal precipitation each year. Objectives did not originally articulate quantitative thresholds for seed production and seasonal precipitation effects, owing to a lack of literature support for them. Objectives for perennial grass recovery were similar for non-seeded areas (referred to as a "natural recovery"), except that the threshold basal diameter was increased to 10.16 cm (4 inches) for bunchgrasses (which presumably were mainly from resprouting plants). In application, the number of plots that had perennial grasses with seed heads and roots deeper than EAGs were compared to the total number of plots in the area of concern. These objectives for grass seeding were based on the limited amount of published science available, and this dearth of information presented another source of uncertainty to the monitoring and assessment. Uncertainty resulted from either limited reproduction of evidence either within or among studies, in measurement technique (e.g., whether cover measurements included previous years' biomass), and from how well the thresholds would apply to different species and environmental conditions (e.g., site climate or weather).

For aerial-broadcast seeding of shrubs and forbs, the objective result was an average of 1 plant per 10 m^2 (108 ft^2) in *suitable areas*. The "suitable area" qualification was important because it formally acknowledged that emergence of these seeded species would be variable and patchy, and that the assessment should emphasize success as establishment primarily where sagebrush could reasonably be expected to establish. Supporting literature to quantitatively define "suitable areas" was not available at the time, however the resulting monitoring data provided considerable insight on factors that promote or inhibit sagebrush recovery. A specific density objective was not set for the relatively small areas that received sagebrush plantings and thus was not part of the broader monitoring implemented by the USGS, but land managers in the study area generally anticipate approximately half of outplants survive. Objectives for enhanced forb seed mixes were 0.5 plant per 10 m^2 (108 ft^2) in suitable areas, and >40% survival of planted sagebrush after two years. For herbicide applications, the objective was average foliar cover of EAGs ≤ 20%.

Sampling and data techniques used

The sampling methods were field-based and quantitative measurements of plant cover, density, size, and root extension or recording general level of seed production that were specific to treatment objectives. Additionally, nominal ratings or coarse measurements of soil-surface conditions, indicators of livestock or wildlife [greater sage grouse, rabbits (*Brachylagus idahoensis*; *Sylvilagus sp*.), hares (*Lepus sp*.), deer (*Odocoileus hemionus*)], and pathogens were recorded because of their ease of incorporation and value in explaining plant and ecosystem responses. Most techniques for monitoring non-forested upland plant communities are time-intensive and are suited primarily for detecting temporal trends over longer periods of time for a low spatial density of plots, such as the field methods used BLM Assessment Inventory and Monitoring (AIM) strategy. Methods for the AIM strategy involve measuring vegetation cover using line-point intercept on three relatively long transects, belt transects for density, measurements of bare soil gaps, and many other optional features that require several hours for a team to sample a plot. A quantitative sampling-effort analysis available from a nearby landscape indicated that 2000 plots across the burned area were required to determine what cover values represent 80% confidence intervals around the mean cover of dominant plant types, specifically bunchgrasses and EAGs (CI; equivalent to 1 plot/54 ha, [1 plot/133 acres], see Appendix). Methods were needed that would enable sampling of many plots over a large landscape in a short amount of time. Sampling locations were determined using a stratified-random approach, using the 1 plot per 54 ha plot density along with exclusion zones along roads and other site factors that could cause plots to not be representative of the area around them. Specifically, locations were rejected if they were in areas with slopes steeper than 40 degrees, occurred within 18 m (59 feet) of roads or 400 m (1312 feet) of a water source (thereby avoiding intense livestock impacts); or if cobbles, rocks, or trails made up >20% of the area.

Up to 20 concurrent field technicians collected data during the monitoring campaigns, with sampling staggered across the elevation gradients in effort to collect data at the time of peak biomass, during the few months each year when deciduous or EAG vegetation is green. Data were collected into Survey123 in ArcCollector (ESRI, Redlands CA) and compiled into a geo-database, from which the field data were downloaded and entered into a Microsoft Access database and subject to processing and quality control screening.

Considerable advance thought and planning was invested into a system of quality assurance for data collection/inputs and quality control of data outputs[22] to ensure that data would be transparent, easily retrieved, reliable, and ultimately able to serve as the basis for pivotal decisions regarding re-treatments or grazing resumption. For possible contested decision making, the data needed to be able to withstand scrutiny, and moreover the data were a feature that could build trust and appreciation for objectivity among the stakeholders, managers, and scientists. A "10% rule" was applied for all data for quality control: after the final stages of data rollup, 10% of data were randomly selected and recomputed from raw data. If any errors were detected, they were fixed, the source of the error was determined with attention to whether the error source was systemic. Additionally, BLM personnel independently reviewed all final data for inconsistencies. Quality assurance measures prior to data collections included 1) establishment of both monitoring plans and detailed protocols that were updated with iterative reviews and revisions by multiple BLM and USGS participants, 2) production of "A Field Guide to the Soda Wildfire Flora"[23] along with plant taxonomy training sessions provided by local botanical authorities, 3) uniform training sessions required of all technicians each year, 4) carefully designing the digital menus for which data were recorded to provide uniformity in responses and, for many variables, providing redundancy that could be used to check for errors, and 5) periodically having technicians independently measure a small number (3-5) of the same test plots to allow comparison of their assessments and to estimate a standard error attributed to measurement teams. As an example of redundancy, two different methods of estimating plant cover were used (visual estimation on a large plot and grid-point intercept on a photo of a small plot) to compare the results. Another critical assurance feature was the extraction of cover data from photographs that were archived and easily retrieved for data review.

At the coordinates for each plot, perspective photographs were first taken in four cardinal directions, to aid interpretation by data end users and at two central plots, for the purpose of quantifying community cover, two aerial photos were captured from 2 m height of 2×3 m ground areas (6.6×9.8 feet; Figs 3, 4, see Germino et al.[24,25] and Applestein et al.[26] for more overall monitoring method detail; 100 grid points total per plot were digitally analyzed using grid-point intercept to species).[26] Species lists were recorded for each 2×3 m (6.6×9.8 feet) phtoto area and the surrounding 13-m (42.7 foot) radius area (the latter was referred to as a "rapid assessment"), as well as unguided visual estimation of cover by function group in the 13-m (42.7 feet) radius plot. A frequency density method was used to quantify density (plants/area) of shrubs (by height class), seeded forbs, and select plants of interest (e.g., exotic forbs, in one sampling year), in which the number of target plants were detected in the first area in which there were at least 3 individuals, starting with the inner 1 m^2 (10.8 ft^2), then to a circular area with radius of 5.5 m (18 feet), and so forth to a radius of 18 m (59 feet; ~1000 m^2, [0.25 acres]). Density of grasses in drill-seeded areas was measured in three 1-m^2 locations (Figs. 3 and 4).

Next, grass traits were measured on the first 5 perennial bunchgrasses encountered (excluding the small-statured Sandberg bluegrass) using the frequency-density approach, including height (to tallest leaf), basal diameter, percent of basal area killed by fire, and percent of grass plants producing seed by species (binned, <50% of plants, 50-75%, >75%).

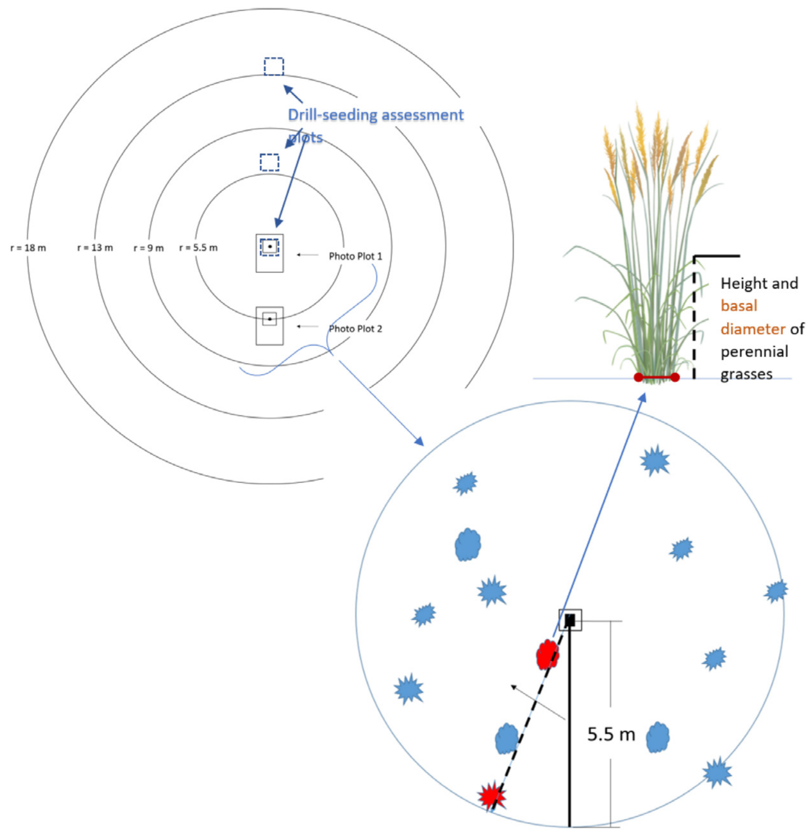

Figure 3. Spatial layout of the primary variables sampled for the Soda Monitoring. Top: Two 2×3 m rectangle areas captured in aerial photographs (see Fig. 4), three 1×1 m areas in which grasses from drill seedings were measured, and concentric circular areas that density of shrubs and forbs were measured in. Right: the method for finding the first five bunchgrasses to measure basal diameter and height (upper right drawing).

The depth and lateral extension of perennial grass roots were measured in drill seeded areas and for a limited number of other contexts in the first three years of monitoring. Depth of EAG roots were also measured for a limited number of plots and years, and presence of pathogens on cheatgrass were also measured.

Additional measurements that varied by year included recording of scat presence from cows, deer, greater sage-grouse, and rabbits; percent of grasses that appeared to have been grazed within a 12-m (42.6 feet) radius plot area. Soil traits recorded included the "pedoderm" classification, which is the characteristics of the soil surface (e.g, biocrust, erosion pavement, base soil) that very strongly affect germination and vegetation recovery.[24,27] Another soil trait was soil-patch connectivity known as "resource retention" classification and is an indicator of ecosystem water and nutrient functioning.[27]

All combined, these methods provided the measurements needed to address the objectives and supplemental information to explain the vegetation responses and their ecosystem impacts, with a focus on recovery of perennial plants or invasion by EAGs.

Examples of insights from the sampling, for sagebrush and exotic annual grasses

The higher density of sampling in the Soda Megafire monitoring has improved the spatial "grain" with which we understand the relationships of key vegetation types among each other and to either environmental variation or treatment effects. The resulting dataset is among the only available that can quantify what "suitable microsites" are for recovery of sagebrush or forbs. Additionally, the fine grain of these time-series allows for concise tests of the assumptions made for setting thresholds. The relatively rapid availability of fine-grained data also allowed identification of re-treatment opportunities within the critical first post-fire year, such as re-application of herbicides, and more importantly provided the information about variability among and within pastures to guide grazing resumption decisions. Some of the more transformative knowledge advancements required time to develop and be peer-reviewed and accepted, and thus are intended to contribute to more future ESR efforts on other wildfire areas.

The greater detection efficiency of the sampling revealed that the abundance of small, newly established sagebrush was greatly enhanced by seeding, or by fertile-island microsites where sagebrush existed before fire, or by features of the soil-surface "skin" (e.g., whether covered by bare grain soil, crusts, etc), and, as was previously known, elevation.[24] Additionally, the data reveal several relationships among recovery of dominant species to be more complex than initially assumed, such as a hump-shaped relationship of sagebrush to perennial-bunchgrass abundances[24] rather than the traditionally perceived negative relationship.[20] The hump-shaped relationship would be expected if both sagebrush and peren-

Figure 4. Examples of photos used in monitoring. Top: perspective landscape photograph. Bottom left: capturing aerial photograph from 2 m height. Bottom right: example of the resulting aerial photograph to be digitally analyzed using grid-point intercept.

nial grasses benefitted from incrementally better growing conditions until an optimal perennial grass cover is evident (which was 40% cover, in this case). Above this optima, additional perennial grass abundances appear to inhibit sagebrush recovery.

The sampling effort also detected initial sagebrush establishment where it was seeded into areas with warm and dry soils (mesic and aridic soil temperature and moisture classes, respectively), which are generally deemed to be unresponsive to sagebrush seeding,[7] but no other published reports used the intensity and timing of sampling used on the Soda Megafire monitoring, and thus these other reports could not have detected the important patterns revealed. A classification and regression tree (CART) was established from these data that provided mappable, quantitative criteria for identifying what the "suitable microsites" are for sagebrush recovery. While these findings were not (and could not have been) available in time to guide most of the sagebrush seeding efforts, the information had application to determination of whether sagebrush seeding was successful or not. For example, where sagebrush was seeded into areas lacking suitable microsites, a lack of subsequent sagebrush recovery would not necessarily imply a failure to meet objectives. The information could be used to create maps in other, newer burned areas that identify areas where sagebrush seeding is more likely to be successful.

In addition to these monitoring-enabled advances in understanding sagebrush recovery, advances were made in understanding natural and management-treatment controls of EAG invasion, and which variables could be measured to best predict vulnerability of sites to EAG invasion after fire.[25,29,30] Because land treatments are not applied randomly to burned areas, correctly selecting untreated areas as controls is both important but often challenging because of the myriad site factors affecting EAG and other vegetation that must be similar among the treated and control areas in order to generate a fair and unconfounded comparison. The high density of plots across the landscape provided a rich set of candidate control plots to use for comparison, leading to more resolute comparisons of EAG response to herbicide applications.[29] The resulting data revealed that imazapic spraying could be deferred until after the initial greenup (instead of immediately applying to freshly burned soils), allowing managers to observe the initial vegetation recovery and reaping a benefit of greater soil stability and less risk of herbicide drift off-site on eroding soils.[29] Moreover, there was little evidence of negative effects of the delayed spraying on perennials that had already resprouted or germinated, thus indicating a clear prospect for combining a phased seeding or planting with herbicide application provided that initial recovery of EAGs was less than a threshold 40% cover[29]. Having many plots also provided the statistical power to elucidate key causal relationships between EAGs and factors such as natural pathogens, specifically head smut (*Ustillago bullata*) that can obliterate cheatgrass seed crops.[31] Restorationists have considered these pathogen outbreaks as natural bio-herbicide opportunities. The annual resampling in the Soda Megafire monitoring revealed that head smut abundances could be predicted by previous-year abundances of cheatgrass, distance to unburned refugia, and warm-wet weather, but the abundance of the pathogen did not diminish subsequent abundances of cheatgrass.[31]

Neither the novel monitoring of perennial grass roots nor the traditional "tug test" (resistance of grass root to upward pulling of shoot) were as strong a predictor of EAG invasion as were basal diameter (diameter of root-foliage interface crown) and the spacing of bunchgrasses as quantified by size of basal gaps (size of bare soil patches between perennial grasses).[25] Furthermore, the detail in the relationships of EAGs to interspace gaps helped refine the apparent threshold diameter of gaps for EAG dominance (~60 cm).[25] These insights were useful in their preliminary stage for helping managers interpret how well the vegetation data satisfied the treatment objectives and are in consideration for application to monitoring in other DOI programs.

"Heat maps" or gridded maps of the presence or abundance of key dominant species are one of the most useful ways to represent vegetation recovery on large, burned areas to inform management, and modeling is required for this (e.g., Fig. 5). The robust Soda Megafire monitoring data provided an opportunity to compare and contrast the different approaches that could be used for making the predictive models.[28] The analysis was intended to help researchers and managers identify how to create the most informative vegetation recovery maps based off of whatever field sampling they have available (either intensive like for the Soda Megafire or relatively sparser sampling in other ESR efforts), along with digital geographic data that is available for all areas (typically grid-

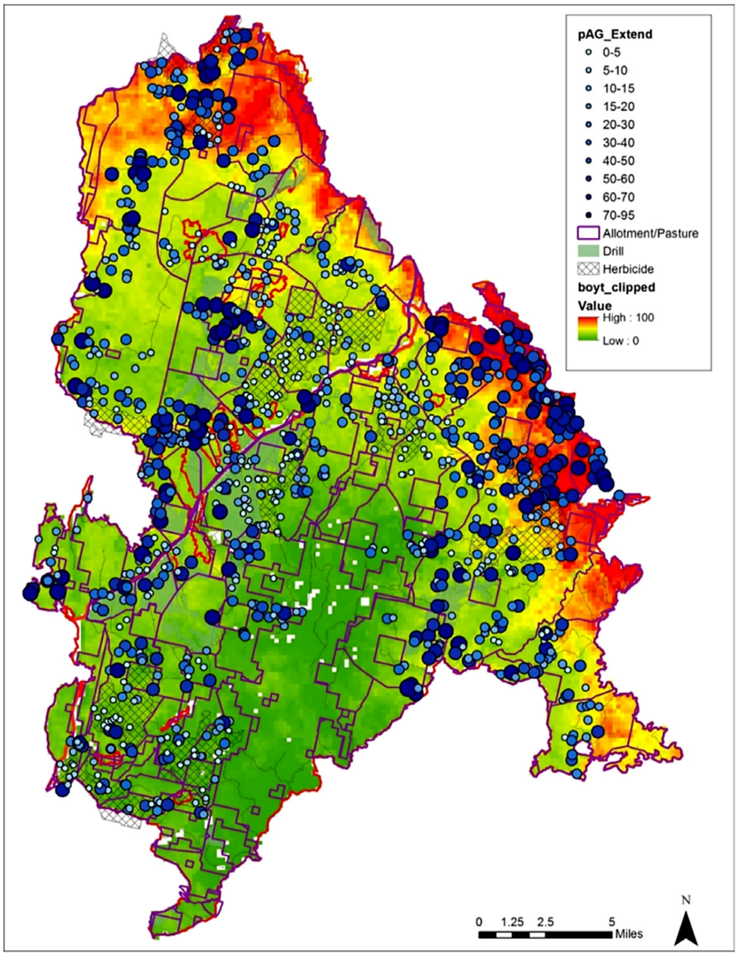

Figure 5. Annual grass abundances in the initial greenup following the 2015 Soda Megafire. The size and blue-color saturation of round symbols shows the percent cover of annual grasses as measured by the "rapid assessment" of ~1000 plots (pAg). Background colors shows the estimates of the "Real-Time Cheatgrass Cover" from the months just prior to the fire (Boyte and Wylie[32]; "boyt" in the legend).

ded, e.g., elevation, soils, climate). Specifically, Barnard et al.[28] evaluated 11 modeling frameworks for creating gridded maps of sagebrush recovering on the Soda Megafire area, comparing readily available machine learning, inferential (hypothesis testing, e.g., with general linear models), and ensemble (i.e., multiple) approaches. Model inputs in Barnard et al.[28] included various combinations of field monitoring and/or digital geographic data. The exercise revealed that the best modeling approach was indeed based on the field monitoring data. More importantly, Barnard et al.[28] revealed that agreement between the different modeling approaches will vary across the burn area (for predicting sagebrush) as a function of precipitation, dominance of EAG grasses, and microsite patterning. Thus, uncertainty in how post-fire vegetation varies between field-sampling locations can be addressed with predictive modeling, though the reliability of modeling outputs will likely vary among areas within a megafire scar.

Validation of remotely sensed models of post-fire vegetation

Land managers commonly ask if remote sensing can be used as a less expensive means for monitoring vegetation outcomes than the field-based approach used here, either pre- or post-fire. Pre-fire vegetation information is valuable for stating objectives, planning treatments, and managing expectations for the treatments. There is currently no remote sensor able to distinguish bare soil adequately or penetrate through overstory foliage to allow measurement of the critical variables of initial emergence of sagebrush, basal diameters of bunchgrasses, or area of basal gaps. However, percent cover of the top plant canopy by functional group and sometimes species (e.g., sagebrush) is detectable by overhead sensors. Available gridded geographical data include coarse plant community classifications available from LANDFIRE (30 m pixel resolution, accuracy unknown), or the fractional abundances of different cover types produced from models of satellite imagery such as Landsat or MODIS. Examples include the Real Time cheatgrass or herbaceous annual herb cover maps,[32] USDA Rangeland Assessment Platform (RAP[33]) or National Land Cover Database maps that are now produced for most years (NLCD,[34] now referred to as RCMAP). These gridded vegetation data would seem invaluable for rapid assessment of megafire areas, but it is difficult to know their accuracy because the validation would require field data measured at the scale at which the satellite measures the landscape, (i.e., across the entire area in large pixels, with reliable application meant to not be individual pixel values [points on the ground] but rather clusters of pixels covering larger areas). Because the Soda Megafire monitoring data are among the densest ever measured for a large landscape and because the collections occur at about the same time period the satellite data are captured, the data offer a unique opportunity to assess the reliability of spatial vegetation models derived from satellite data.

Relatively high error in quantifying sagebrush recovery after wildfires with data such as the NLCD is both expected because of the scarcity of sagebrush after fire, and indeed has been reported by Applestein and Germino.[35] For example, cover estimated by the NLCD was 6.5 percentage points greater than field estimates of sagebrush (which had maximum values near 20% cover) in the years just after fire, and this 6.5% overestimate occurred even where the field data indicated sagebrush was absent, or nearly so.[35] On the Soda Megafire area specifically, the NLCD data mapped 80% of the field plots that had no sagebrush as having 1-5% sagebrush cover, in 2016. Thus, these remotely sensed data must be used with great caution if they are used to make inference about spatial variation in vegetation composition within burn areas.[35] Preliminary analyses suggest that the Real Time cheatgrass map or RAP and related products are most accurate for determining average cover at scales larger than a radius of about 2.5 km (1.5 miles), which is greater than the size of most pastures and other management units (Applestein et al., unpublished data). The reliability of the models likely increases when their information is used to represent relative change in plant cover over time or spatial variation at coarser scales (e.g., among but not within burn areas).

Additionally, the relatively large discrepancy of vegetation cover estimates compared to field data benchmarks suggest that the best application for remote sensing will likely be representing average conditions (cover by functional group) across entire burn areas and avoiding the errors likely to emerge when comparing different areas within a larger burn scar.

Real-time use of the monitoring data to inform post-fire decisions, including on grazing resumption

The hallmark of adaptive management is using observations (data) collected on treatments or other actions to modify or improve follow-on actions. An example of this occurred during the first post-fire growing season (2016), where a relatively rapid assessment of EAG emergence patterns was made across the burn area in May and June and the resulting information was used to inform additional treatment needs in that same year. A top priority of the managers was to detect and act on areas of increased EAGs, and so the rapid assessment protocol was used to estimate EAG cover on 1,000 plots, in a short period of two months from the start of sampling (Fig. 5). The resulting information was used to identify and justify additional herbicide applications, which were shown to have reasonable short-term effectiveness if EAGs had not already exceeded a foliar cover of about 40%.[29]

Monitoring data were used to inform grazing resumption decisions for each pasture, with data collection, processing, and summarization made to match the time at which grazing resumption decisions needed to occur. BLM managers prepared documents for each pasture that summarized the monitoring findings relative to treatment objectives and included representative site photographs. This information was shared openly through field trips and other communications with permittees, stakeholders, the Partners group, and BLM's "Interdisciplinary Teams" assigned to make recommendations on the decisions. Managers or their agents requested to verify the data by reviewing the methods, data, or aerial photos from which cover was determined, which was easily facilitated. The data were used to keep pastures closed or alternatively permit livestock grazing resumption prior to treatment objectives being met from the monitoring data. Other factors were considered in determining grazing resumption, in addition to the monitoring data and objectives. The objectives were developed based on best available data but assumptions regarding them were nonetheless required. The monitoring data are currently being used to formally evaluate how the recovery patterns by 2020 compare with the quantitative thresholds measured in 2016-2018, before or as livestock were returned to pastures (e.g., thresholds for perennial grasses: mean cover >20%, mean basal diameter > 7.6 cm (3 inches), density > 3 plants/m^2 (> 3 plants/10.8 ft^2).). The resulting information can be used to refine the objectives for future ESR efforts.

Broader considerations

The measurements of vegetation recovery after the Soda Megafire are an example of adaptive monitoring in support of the adaptive management loop because 1) the monitoring was structured around clear and quantitative objectives set by a broad interagency partnership, customized to the different restoration treatments that began implementation prior to monitoring, 2) the data were processed, summarized, and interpreted in a timely fashion, 3) the findings were used to guide follow-on management decisions such as with additional herbicide treatments and grazing resumption, and 4) the cycle was repeated iteratively, including new treatments, and monitoring methods were adjusted as the project developed. The workflow for monitoring produced for the Soda Megafire strengthened management decisions by enabling the decisions to be more 1) objective, based on how the measured vegetation recovery (including variance) related to quantitative thresholds for desired plant recovery, 2) transparent and tractable, with strict adherence to monitoring protocols made available to all interested stakeholders and the ability to readily retrieve plot photos for verification, 3) broadly accepted by the diverse participants, as a result of open participation in devising objectives, protocols, and data interpretations, and 4) available in time for the key decision making events, which were often within a week or so of data collection. As described above, the workflow was critical for guiding the decisions on grazing resumption for the 105 pastures and was key for decision making on rapid response to emerging EAG outbreaks, for example. While it is unlikely that other ESR projects would use the exact monitoring plan applied to the Soda Megafire, by adopting the basic elements of the workflow, other ESR projects can similarly strengthen the basis for their management decisions.

Persistence required for the time frames of monitoring and adaptive-management projects

In the early planning phases, there was some debate on whether the ambitious Soda Megafire monitoring plan was feasible or could be financially afforded in the ESR project. The monitoring project was planned for five years, and the fifth year of sampling (2020) was completed with as much or more plots and variables measured than originally planned. This success demonstrates that quantitatively defensible monitoring for adaptive management of megafire areas is feasible (i.e., sampling enough plots to achieve the CI threshold defined by the pre-monitoring sampling-effort analyses, and reporting variance along with mean vegetation responses). By feasible, we mean that it was accomplished with a reasonable time and energy expenditure relative to the larger project.

The factors that enabled the persistence of the Soda Megafire monitoring through its planned 5-year duration are useful to consider in establishing adaptive management efforts in rangelands. A high level of personnel turnover in pivotal positions in BLM and DOI was compounded by intermittent uncertainty in annual continuation funding. Relevant personnel changes included the temporary BLM district Soda Megafire monitoring lead position changing three times, the relevant field office managers (Vale and Owyhee field offices) changing at least four times each, the lead of the fire-rehabilitation response programs in the BLM Districts (Boise and Vale) changing at least three times each, the BLM District manager's and State directors changing at least twice, the program lead of the BLM's ESR program changing five times, and the Director of the BLM and Secretary of the DOI each changing at least three times during the five years of the monitoring. The USGS Soda Megafire monitoring leaders, several staff within the Boise District ESR program (including co-author P. Torma), and the BLM Idaho State office ESR lead were the only remaining original staff after 5-years.

Any of these personnel transitions could have led to major change in the project, but yet the project persisted through many months of uncertain future. The persistence was enabled by agency documents such as the ESR handbook, Secretarial Orders, and other guidance documents plus a clear vision and interagency commitment and determination established via co-production by a diversity of participants in the BLM, USGS, and broader Soda Megafire Partners. The network of mutually concerned agencies and their staff provided the needed reinforcement and encouragement to achieve the end goal. Thus, we suggest that co-production confers persistence towards the longer-term, challenging end goals of projects where intensive monitoring and adaptive-management approach are used.

Costs factor into long-term success

The direct costs for monitoring, assessment, and associated communications on the Soda Megafire were approximately $150 per plot per year, which led to total costs that were a small fraction of the total authorized costs for the entire project including treatments. In a 5-year project, the costs will normally increase due to inflation and payroll raises in just about any institution, but there are mitigating factors that could/should be recognized when dealing with the budgeting. In spite of rising cost rates, the general skill and efficiency in planning and implementing monitoring increased each year in the Soda Megafire monitoring, and overall monitoring costs/plot thus decreased each year.

Transferring methods from the Soda Megafire monitoring to other burned areas?

The Soda Megafire monitoring project was not meant to set precedent for monitoring of future burn areas, in terms of setting standards for monitoring. The ESR program must frequently balance investment into post-fire treatments with monitoring. Instead of adopting intensive monitoring throughout a megafire, managers could develop customized monitoring in which sampling intensity is allocated more precisely to specific needs as they vary with fire complexity, size, stakeholder interests, and other factors. Information can be gleaned from the rich Soda Megafire dataset to guide efficient design and implementation of monitoring of these other burned areas, to assist with this, including the variables measured which were most impactful (e.g., basal gap size). Opportunities exist to establish guidance for planning monitoring in light of these factors, in addition to decision making when monitoring cannot provide estimates of vegetation to certain CI threshold levels.

While our sampling methods were oriented to obtaining many quantitative observations in a short period over a large and remote landscape, aspects of our methods may nonetheless confer some utility to other monitoring regimes, such as AIM. For example, users of AIM data may wonder what the appropriate spatial scale is to utilize the relatively sparse AIM data for their areas of interest, which can only be known through the type of sampling-effort curve analysis that guided the Soda Megafire monitoring. For a particular landscape of interest and in short order, a user of AIM data could apply our rapid-assessment technique to provide the oversampling needed to construct a sampling effort curve and thereby determine whether the number of AIM plots in the landscape can provide the desired confidence threshold or determine how many more plots would be needed to satisfy their requirements. The sampling effort curves for the Soda Megafire monitoring generally will suggest that ESR efforts on other fires are more likely to obtain the type of rapid "snapshot" of vegetation recovery over large areas if they can redistribute the time and effort required for full AIM monitoring to a greater number of plots.[25] To accomplish this, each plot would not be measured as intensively (e.g., this could include reducing the standard three line-point intercept transects to one or two per plot) and instead measuring more plots. Additionally, some of the variables we measured, including basal diameter of bunchgrass or pedoderm classification could be easily incorporated into any ESR monitoring and would provide useful insights.

Strengthening science-management partnerships: an important outcome

The building of mutual understanding and trust between scientists, managers, livestock operators, and other stakeholders through participating in the project together is a key benefit that has enhanced readiness to address management of other burned areas and needs regarding fire, invasives, and restoration. The interactions among the Soda Megafire Partners have also helped identify science information needs by managers of burned areas and helped direct transfer of new science to the involved managers and agency offices. Science transfer to participating managers was built into the co-production of this ESR project, but expanding science transfer to the programmatic (e.g., national) scale is more challenging and there are opportunities for improvement. For example, it is unclear how well the transferable insights from the Soda Megafire project have been adopted in subsequent ESR efforts in other districts and states, and a follow-on USGS/BLM project is underway to enhance sampling of other megafires in the region and provide the data needed to formally evaluate transferability. In addition to publications and presentations to agencies or professional groups, personal communication networks, sharing of staff assignments for BLM ESR and now USGS specialists to assist ESR teams elsewhere in the sagebrush steppe, the national ESR's annual "lessons learned" meeting, and the Great Basin Fire Exchange (https://greatbasinfirescience.org/) are all key means for information exchange.

Declaration of Competing Interest

M.J.G. writes the Browsing the Literature column for *Rangelands*, but he was not involved in the review and decision process for this manuscript. The content of sponsored issues of Rangelands is handled with the same editorial independence and single-blind peer review as that of regular issues.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rala.2021.12.002.

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