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A Synopsis of Short-Term Response to Alternative Restoration Treatments in Sagebrush-Steppe: The SageSTEP Project

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Abstract

The Sagebrush Steppe Treatment Evaluation Project (SageSTEP) is an integrated long-term study that evaluates ecological effects of alternative treatments designed to reduce woody fuels and to stimulate the herbaceous understory of sagebrush steppe communities of the Intermountain West. This synopsis summarizes results through 3 yr posttreatment. Woody vegetation reduction by prescribed fire, mechanical treatments, or herbicides initiated a cascade of effects, beginning with increased availability of nitrogen and soil water, followed by increased growth of herbaceous vegetation. Response of butterflies and magnitudes of runoff and erosion closely followed herbaceous vegetation recovery. Effects on shrubs, biological soil crust, tree cover, surface woody fuel loads, and sagebrush-obligate bird communities will take longer to be fully expressed. In the short term, cool wet sites were more resilient than warm dry sites, and resistance was mostly dependent on pretreatment herbaceous cover. At least 10 yr of posttreatment time will likely be necessary to determine outcomes for most sites. Mechanical treatments did not serve as surrogates for prescribed fire in how each influenced the fuel bed, the soil, erosion, and sage-obligate bird communities. Woody vegetation reduction by any means resulted in increased availability of soil water, higher herbaceous cover, and greater butterfly numbers. We identified several trade-offs (desirable outcomes for some variables, undesirable for others), involving most components of the study system. Trade-offs are inevitable when managing complex natural systems, and they underline the importance of asking questions about the *whole system* when developing management objectives. Substantial spatial and temporal heterogeneity in sagebrush steppe ecosystems emphasizes the point that there will rarely be a “recipe” for choosing management actions on any specific area. Use of a consistent evaluation process linked to monitoring may be the best chance managers have for arresting woodland expansion and cheatgrass invasion that may accelerate in a future warming climate.

Key Words: cheatgrass invasion, ecological resilience, ecosystem management, environmental gradients, sagebrush restoration, woodland expansion

INTRODUCTION

This synopsis highlights the initial ecological effects of sagebrush steppe restoration treatments implemented as part of the Sagebrush Steppe Treatment Evaluation Project (SageSTEP), and summarizes socio-economic results related to restoration efforts. SageSTEP was designed to provide treatment-related information on how to address the rapidly changing condition of sagebrush (*Artemisia tridentata* spp.) steppe ecosystems in the US Intermountain region (McIver et al. 2010). Over the past 100 yr, fire suppression, inappropriate livestock grazing, invasion of exotic plants such as cheatgrass (*Bromus tectorum*), and expansion of native conifers (western juniper [*Juniperus occidentalis*], Utah juniper [*Juniperus osteosperma*], single-leaf piñon pine [*Pinus monophylla*], Colorado piñon pine [*Pinus edulis*]), have contributed most to the declining condition of sagebrush ecosystems within the region (Pellant 1994; Miller et al. 2008; Balch et al. 2012). At sagebrush steppe sites that do not support trees, cheatgrass and other exotic species have become more dominant at the expense of native perennial bunchgrasses, in some locations shifting fire return intervals from >50–100 years to <20 years, and vastly increasing the number of fires and total area burned (Whisenant 1990; Miller et al. 2011; Balch et al. 2012). At sagebrush steppe sites into which piñon and juniper woodlands have expanded and displaced sagebrush, other shrubs, and herbaceous vegetation, fire return intervals have shifted from 10–50

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years to >50 years, and significantly increased mean fire severity (Miller and Heyerdahl 2008). Under current climate conditions, both cheatgrass and piñon and juniper trees have the potential to dominate an even larger area in the Great Basin and surrounding lands (Wisdom et al. 2002), and global warming is likely to exacerbate this trend (Neilson et al. 2005; Miller et al. 2011).

Federal, state, and private land managers and owners have for many years attempted to arrest the conversion of sagebrush steppe communities into woodland and annual grassland and to restore native herbaceous communities by applying treatments such as prescribed fire, mowing, chaining, cutting, mastication, or herbicides. Restoration practices have the potential to alter fuel beds and decrease future fire suppression costs (Taylor et al. 2013), lower competitive suppression of perennial bunchgrass species, and decrease longer-term risk of cheatgrass dominance (Chambers et al. 2014a). Substantial published information exists on the efficacy of such treatments in sagebrush steppe, but most studies are site-specific, short-term (Miller et al. 2013), and focused on few variables. Recognizing this, the Bureau of Land Management, in collaboration with the Joint Fire Science Program (JFSP), solicited sagebrush steppe scientists and managers to design a broader study that would provide multisite, multidisciplinary, long-term information on outcomes of alternative treatments over a range of ecological conditions, and that would also provide insight on cost and public acceptance of management practices. A planning grant was provided by JFSP in 2003 to design SageSTEP, and the study was ultimately funded by JFSP in 2005.

In this synopsis, we will briefly describe the SageSTEP study, and then present short-term results in the context of five key themes that the study was designed to address: 1) resilience and resistance, which are key concepts in state-and-transition models; 2) effectiveness of fire vs. fire surrogates, which differ in suitability depending on the situation; 3) trade-offs among key response variables, which are important for decision-making by managers; 4) temporal scale of response in different variables; and 5) heterogeneity in time and space, which is the source of much of the variation found in the literature. Finally, we also briefly discuss the SageSTEP Project as a model of a multisite, multivariate, and long-term study intended to provide information more useful to managers than traditional single-site, single-variable, short-term studies.

EXPERIMENTAL DESIGN

SageSTEP consists of 21 widely distributed sites, arranged in two parallel experiments, both conducted in ecosystems formerly dominated by sagebrush in the overstory and by herbaceous perennial vegetation in the understory. The experiments emphasize the major restoration challenges in the region: invasion of cheatgrass into drier Wyoming big sagebrush communities, and expansion of piñon and juniper into higher-elevation sites.

The "sage–cheat" experiment examined cheatgrass invasion at seven dry, lower-elevation sites located in five states (Fig. 1). Each site was a statistical block, comprising one 20–80-ha plot as unmanipulated control, and prescribed fire, mowing, and herbicide applied across the other three plots. Plot-level treatments were intended to reduce the sagebrush overstory in an effort to alter the competitive balance between perennial bunchgrasses and cheatgrass in the understory. Although treatments that reduce sagebrush may seem to contradict the management goal of preserving sagebrush steppe ecosystems, they may in some cases lead to more desirable vegetation states in the long run, if they stimulate native perennial herbaceous plants relative to exotic annual plants. Within each plot, between 18 and 24 subplots (0.1 ha) were established, within which were measured most response variables. Prescribed fire was applied first, from May to October 2006, 2007, or 2008; fire blackened about half of each plot (Table 1). Once fire was implemented at each site, mowing and herbicide treatments were applied to the other plots within 8 mo. For the mowing treatment, rotary mowers were set at a height that removed and distributed approximately 50% of sagebrush cover. For the herbicide treatment, tebuthiuron was applied over the entire plot at a rate intended to remove 50% of the overstory. Finally, the pre-emergent herbicide imazapic was applied after plot-level treatments to one-half of the subplots within each plot; at low rates, imazapic is intended to target annual plants.

The "woodland" experiment examined piñon and juniper expansion at 14 higher-elevation sites located in five states (Fig. 1). The woodland experiment was divided into three regions: sites dominated by western juniper (six sites in Oregon, southwestern Idaho, and northern California), sites with a roughly equal balance of both piñon and juniper (four sites in Nevada), and sites dominated by Utah juniper (four sites in Utah). Each site was a statistical block; one 10–25-ha "core" plot served as a control, and prescribed fire and clear-felling were applied across the other two plots; at the four Utah woodland sites, mastication was applied in an additional plot. Plot-level prescriptions were intended to remove trees in an effort to stimulate the shrub and herbaceous understory. Within each plot, we established 15 measurement subplots (0.1 ha), spanning a condition gradient defined by the relative dominance of trees within each subplot. Prescribed fire was applied first, between August and November of 2006, 2007, or 2008 (Table 1), with clear-fell and mastication (Utah sites only) treatments implemented within 6 mo.

VARIABLES AND DISCIPLINES

SageSTEP measured treatment response in a wide variety of ecological variables, and also evaluated socio-political and economic variables related to sagebrush steppe restoration. Vegetation variables were measured at the subplot level, and included cover and density of trees, shrubs, forbs, grasses, biological soil crusts, and bare ground, and gap size (distance between perennial plants). Fuel mass and fire risk reduction were evaluated by measuring the fuel bed within all subplots, including standing dead wood, surface wood, litter, duff, and live fuels. We measured soil water and temperature, nitrogen availability, carbon, cations, and anions at three to six locations within each plot, also chosen to span the condition gradient across each plot. Bird communities were studied at woodland sites by conducting point counts within each of the 14 woodland plots, and by conducting intensive demographic work at five pairs of > 400-ha plots (prescribed burned and control), at the

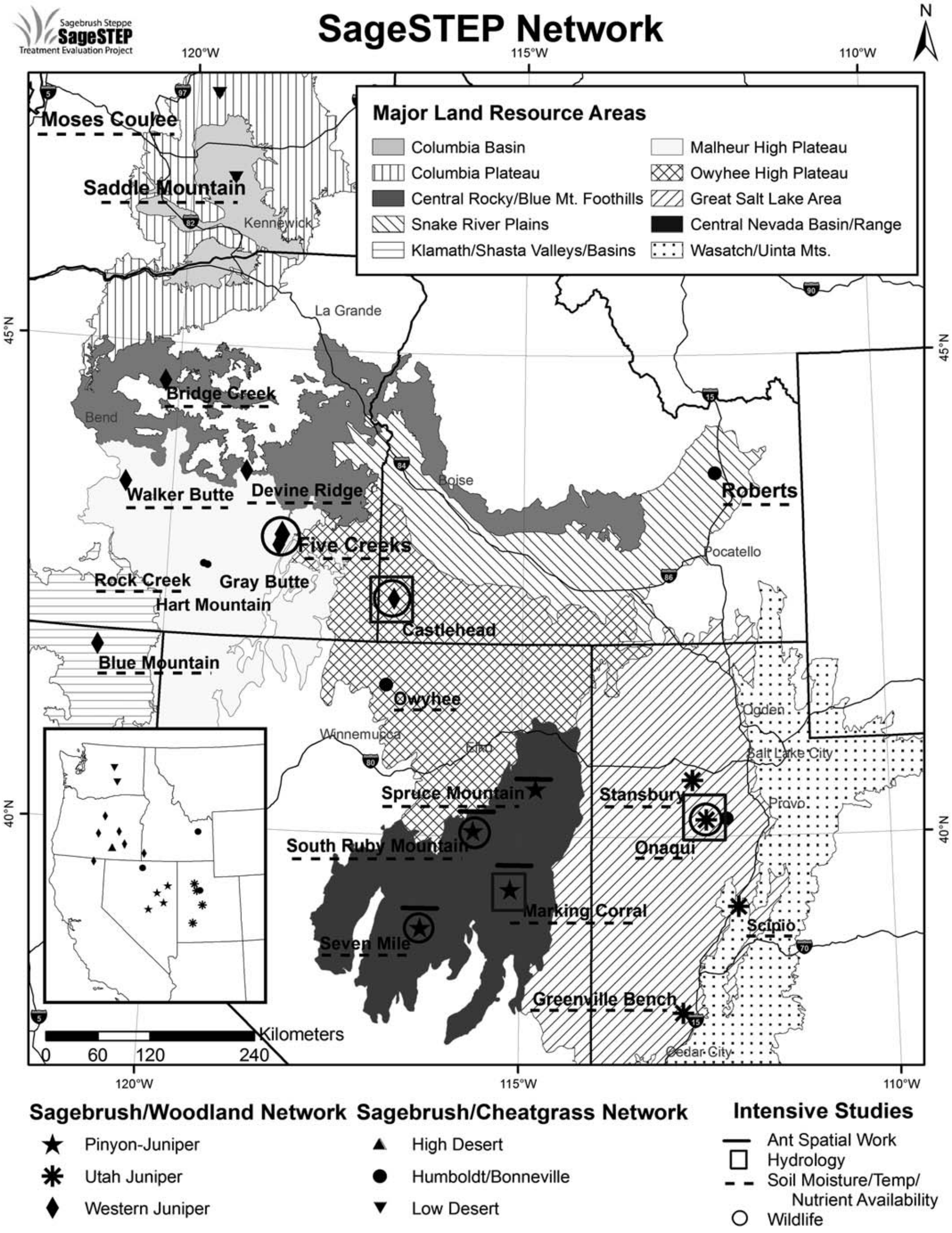

Figure 1. Location of SageSTEP study sites in Great Basin and surrounding sagebrush steppe lands, within major land resource areas (Natural Resources Conservation Service).

Castlehead, Five Creeks, Onaqui, Seven Mile, and South Ruby sites. Butterfly abundance and richness were estimated at the plot level, by cruising 1 000-m belt transects between one and three times per year prior to treatment (2006), and up to 6 yr after treatment (2012); butterfly host plants and nectar sources were noted if observed within or near a plot, or along a transect. Concerns about runoff and erosion were addressed by studying hydrological response within adjacent plots at three woodland sites: the western juniper site at Castlehead, the piñon–juniper site at Marking Corral, and the juniper–piñon site at Onaqui (Fig. 1). SageSTEP hydrological research used artificial rainfall experiments to evaluate how tree removal treatments influenced runoff and erosion, and to identify which conditions might exacerbate those effects. The socio-political component addressed perceptions and values associated with feasibility of and acceptance of treatments that might constrain implementation of practices. The goal of the economics research was to provide a comprehensive understanding of the trade-offs and incentives that face decision-makers as they consider whether and how to treat sagebrush steppe lands.

Fuel Treatment Effectiveness

All treatments had effects on the fuel bed by removing, reducing, or redistributing woody vegetation. In several cases,

Table 1. Sagebrush Steppe Treatment Evaluation Project site information, including site acronym and name, state, year treated, percent plot area burned in prescribed fire (parentheses after year), elevation, slope, aspect, current native vegetation, precipitation zone, surface soil structure, and soil temperature/moisture regime.

Site[1], State	Year treated	% Burn	Elevation (m)	% Slope	Aspect	Dominant tree/ shrub species	Current native vegetation (precipitation zone)	Surface soil structure	Soil temperature/ moisture regime
Woodland experiment (sites at which treatments targeted reduction in tree cover)									
BM: Blue Mt, CA	2007	75	1 500–1 700	5	N	Western Juniper	Mountain Big Sage, ID Fescue, Sandberg bluegrass, Bluebunch wheatgrass (12–16'')	loamy, mixed	frigid/xeric
BC: Bridge Creek, OR	2006	56	800–900	25	NW	Western Juniper	Basin Big Sage, Bluebunch wheatgrass, Sandberg bluegrass, ID fescue (9–12'')	sandy loam	mesic/aridic-xeric
DR: Devine Ridge, OR	2007	62	1 600–1 700	0–8	W	Western Juniper	Mountain Big Sage, Squirreltail, Sandberg Bluegrass, Thurber needlegrass, Idaho Fescue (12–16'')	loamy-skeletal, mixed	frigid/xeric
WB: Walker Butte, OR	2006	77	1 400–1 500	Flat	—	Western Juniper	Mountain Big Sage, Squirreltail, ID fescue, Thurber needlegrass (9–12'')	ashy, glassy	frigid/xeric
MC: Marking Corral, NV	2006	66	2 300–2 400	6–20	NW, NE, SE	piñon-Utah Juniper	Wyoming Big Sage, Thurber needlegrass (12–16'')	loamy-skeletal, mixed	cool mesic/aridic-xeric
SV: Seven Mile, NV	2007	40	2 300–2 500	6–15	NW, E, SE	piñon-Utah Juniper	Mt Mahogany/Mountain Big Sage, Bluebunch wheatgrass, muttongrass (12–16'')	loamy-skeletal, mixed	cool frigid/xeric
SR: South Ruby, NV	2008	40	2 100–2 200	8–30	All aspects	piñon-Utah Juniper	Wyoming Big Sage/Bitterbrush, Bluebunch wheatgrass, Sandberg bluegrass, Thurber needlegrass (12–16'')	loamy, mixed	cool mesic/xeric
GR: Greenville Bench, UT	2007	38	1 750–1 850	2–28	N	Utah Juniper-Colorado piñon	Wyoming Big Sage, Needle and Thread, Bluebunch wheatgrass (10–12'')	gravelly to cobbly sandy loam	warm frigid/xeric
OJ: Onaqui Mt, UT	2006	85	1 700–2 100	2–30	E	Utah Juniper-Colorado piñon	Wyoming Big Sage, Bluebunch wheatgrass (10–12'')	loamy-skeletal, carbonatic	warm mesic aridic-xeric
SC: Scipio, UT	2007	38	1 700–1 800	2–28	W	Utah Juniper-Colorado piñon	Wyoming Big Sage, Bluebunch Wheatgrass (10–12'')	loamy-skeletal, mixed	warm mesic/aridic
ST: Stansbury, UT[2]	2007	95	1 700–1 850	8–30	W	Utah Juniper-Colorado piñon	Mountain Big Sage, Antelope Bitterbrush, Bluebunch Wheatgrass (12–14'')	loamy-skeletal, mixed	cool mesic/aridic-xeric
Sage-Cheat experiment (sites at which treatments targeted reduction in shrub cover)									
OC: Onaqui Flat, UT	2006	79	1 750–1 850	3–4	E	Treeless: Wyoming Big Sage	Wyoming Big Sage/Antelope bitterbrush, Bluebunch wheatgrass, Slender wheatgrass (8–10'')	fine-loamy	mesic/xeric
OW: Owyhee, NV	2008	45	1 700–1 750	0–10	All aspects	Treeless: Wyoming Big Sage	Wyoming Big Sage, Thurber needlegrass, Bluebunch wheatgrass, Squirreltail, Sandberg bluegrass, Wildrye (8–10'')	fine-silty to fine-loamy	mesic/xeric
RO: Roberts, ID[2]	2007	8	1 550–1 600	0–10	All aspects	Treeless: Wyoming Big Sage	Wyoming Big Sage, Bluebunch wheatgrass (8–10'')	fine to coarse-loamy	frigid/xeric
GB: Gray Butte, OR	2008	50	1 450–1 600	0–10	All aspects	Treeless: Wyoming Big Sage	Wyoming Big Sage, Squirreltail, Thurber needlegrass (10–12'')	fine-loamy to loamy mixed	frigid/xeric
RC: Rock Creek, OR	2007	40	1 450–1 600	0–10	All aspects	Treeless: Wyoming Big Sage	Wyoming Big Sage, Squirreltail, Thurber needlegrass (10–12'')	fine-loamy to loamy mixed	frigid/xeric
MO: Moses Coulee, WA[3]	2008, 2009	55	515–530	0–10	S	Treeless: Wyoming Big Sage	Wyoming Big Sage, Bluebunch wheatgrass, Squirreltail, Sandberg bluegrass (10–12'')	loamy-skeletal to coarse-loamy over sandy	mesic/xeric
SM: Saddle Mt, WA	2008	65	262–286	1–5	S	Treeless: Wyoming Big Sage	Wyoming Big Sage, Bluebunch wheatgrass, Indian ricegrass, Bottlebrush squirreltail (8–10'')	coarse-silty	mesic/xeric

[1] Five Creeks and Castlehead avian sites (see Figure 1 for location) described in Knick et al. 2014; Castlehead hydrology site described in Pierson et al. 2014.

[2] Site burned by wildfire after 2007 treatments applied: Stansbury – 2009 (Big Pole Fire); Roberts – 2010 (Jefferson Fire).

[3] Moses Coulee burn treatment applied 2008, followed by mowing and herbicide treatments in 2009.

treatments stimulated herbaceous understory growth. At sage–cheat sites, live shrub biomass (fuel) was reduced by prescribed fire and mowing to averages of 43.6% and 31.2% of pretreatment biomass, respectively (Table 2). Although shrub reduction was similar for fire and mowing, slash fuel mass (10+100-h fuel) was reduced by fire to 39% of pretreatment levels, but increased by mowing to 162% (Fig. 2). Shrub reduction released the herbaceous understory (both invasive annuals and native perennials), with herbaceous biomass increasing in fire and mow plots to 435% and 294% of pretreatment mass, respectively. The herbicide imazapic suppressed response of herbaceous fuel to shrub reduction, with fire plots showing no change and mow plots increasing slightly to 159% of pretreatment levels. Tebuthiuron had no measurable effects on shrub fuel by 2 yr posttreatment, and thus any herbicide treatment effect cannot be attributed to shrub reduction. Overall, with the exception of tebuthiuron, treatments were effectively applied, and thus measured responses can be confidently attributed to experimental efforts to remove, reduce, or redistribute woody vegetation (Table 2).

At woodland sites, all trees within measurement subplots were killed by fire, cutting, or mastication (although some tree sprouting has now occurred). Mechanical treatments had little effect on shrubs, whereas prescribed fire reduced shrub biomass to 5.9% (Phase 1), 9.6% (Phase 2), and 25.1% (Phase 3) of pretreatment levels. Although fire had little effect on slash fuels measured 2 yr posttreatment, mechanical treatments increased slash fuels by more than two-fold overall, with increasingly greater effects at higher levels of initial tree expansion. Tree and shrub removal in fire plots stimulated total herbaceous vegetation, which tripled in Phase 1 and 2 plots, and quadrupled in Phase 3 plots. Tree removal in mechanical plots also caused an increase in total herbaceous fuel to 188%, 261%, and 467% of pretreatment levels in Phase 1, 2, and 3 plots, respectively. In summary, all treatments were successfully implemented at the subplot level in the woodland experiment, which allowed attribution of ecological response to treatment in the vegetation, in soils (chemistry, water, temperature), and for hydrological variables. For butterflies, which were measured only at the plot level, mechanical treatments were effectively applied, but the magnitude of disturbance caused by prescribed fire varied among sites, with plot-level percentage of area burned ranging from 38% to 95% (Table 1). Thus, compared to mechanical treatments, the magnitude of butterfly response to prescribed fire should be judged as conservative (McIver and Macke 2014). For birds, which were also measured at the larger plot scale, prescribed fire was not effective, because between 6% and 24% tree cover remained after treatment, too much for sagebrush-obligate species. Only mastication caused an effective change in habitat as perceived by sagebrush-obligate species, due to the more complete structural conversion of woodland to sagebrush steppe sites (Knick et al. 2014).

Resilience and Resistance

In this study, resilience is defined as the capacity of an ecosystem to regain its fundamental structure, processes, and functions when altered by stressors (like drought), disturbances, or altered fire regimes (Holling 1973; Allen et al. 2005). For sagebrush steppe systems, a key to resilience is the capacity to regain adequate native perennial herbaceous cover given disturbances like fire and mechanical treatments. Resistance is defined as the capacity of an ecosystem to retain its fundamental structure, processes, and functions despite stresses, disturbances, or invasive species (Folke et al. 2004). Retaining adequate perennial herbaceous cover in the face of potential invaders is an important part of resistance in the sagebrush steppe system.

SageSTEP treatments allowed us to assess resilience and resistance for various disturbances and across gradients of tree encroachment or cheatgrass invasion (McIver et al. 2010), and across soil moisture and temperature regimes (Chambers et al. 2014a). Resilience generally increased from warm/dry (mesic/aridic) Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis*) to cool/moist (frigid/xeric) mountain big sagebrush (*A. t.* subsp. *vaseyana*). In particular, 3 to 4 yr after treatment, neither native perennial grasses nor forbs differed from controls in treeless Wyoming sagebrush, but both increased significantly in Wyoming sagebrush/woodland and mountain sagebrush/woodland (Table 2). Resilience after fire was generally lower because of the removal of both shrubs and trees, and resilience was lower on plots that initially had higher cover of trees, due to lower perennial bunchgrass cover before treatment (Chambers et al. 2014a). However, even in plots with high tree cover, bunchgrass cover increased by 3 yr both after fire and after mechanical treatment, and was trending higher with time (Roundy et al. 2014a; Fig.2).

Resistance followed a similar pattern across sites as did resilience, with some exceptions. Wyoming big sagebrush communities had greater climate suitability and higher pretreatment levels of cheatgrass, and were therefore less resistant to invasion after treatment, particularly on soils with low water-holding capacity (Chambers et. al 2014a; Pyke et al. 2014; Rau et al. 2014; Fig. 2). Neither native perennial grass species composition nor big sagebrush subspecies had as much influence on resistance as did soil temperature and moisture regimes. For example, the Stansbury site had relatively low resistance to cheatgrass, despite having mountain big sagebrush as the dominant shrub, because this site is relatively warm and thus susceptible to cheatgrass invasion (Roundy et al. 2014a). In contrast, the other woodland sites dominated by mountain big sagebrush were relatively cool and moist, and typically had high resistance to cheatgrass (Chambers et al. 2014a). Other disturbance factors, such as the application of imazapic and grazing pressure, may mitigate these results somewhat. Imazapic was very effective in controlling cheatgrass in the short term, but because it also impacted perennial bunchgrasses and some forbs, perennials were generally not able to capture available resources any better than without the use of imazapic (Pyke et al. 2014).

The effect of grazing as a disturbance factor presents a more complicated picture, due to the variation among sites in how it is managed. SageSTEP sites were not grazed during the experiment, and thus we cannot comment on how grazing might have influenced resilience and resistance. However, parallel research funded as part of SageSTEP near one of our sites (Hart Mountain), indicated that intensive grazing can decrease both resistance and resilience—even in sites with high native perennial bunchgrass populations—in two distinct ways

Table 2. List of key short-term ecological results and socio-economic results for SageSTEP studies summarized in this synopsis.

Senior author	Ecological site[1]	Years after treat	Variables	Results
Bourne and Bunting (2011)	WY–shrub	2 yr	Live herbaceous biomass—no plateau	↑ Fire and mechanical treatment
			Shrub biomass	↓ Fire and mechanical treatment
			Slash fuel (1 + 10 + 100-h woody)	↓ Fire, ↑ mechanical treatment
			1 000-h fuel	Response to fire and mechanical treatment variable among sites
	WY–PJ + MT–PJ	2 yr	Live herbaceous biomass	↑ Fire, most in Phase 3 and ↑ mechanical treatment only Phase 3
			Shrub biomass	↓ Fire all phases, ↑ mechanical treatment Phases 1 and 2
			Slash fuel (1 + 10 + 100-h)	↓ Fire Phases 1 and 2 only, ↑ mechanical treatment all phases
			1 000-h fuel	Fire generally ↓ but variable among phases, mechanical treatment ↑ all phases
Roundy et al. 2014a	WY–PJ, MT–PJ	2, 4 yr	October–June precipitation	100–600 mm over 4 yr across woodland sites; varied 2× over years at most sites
			Soil moisture: temperature regime	Warm/wet: BC, ST, SC; cool/wet: DR, WB, BM; warm/dry: OJ, GB; cool/dry: SR, MC, SV
			Soil wet days	Cut plots ↑ fall–spring, burn plots ↑ winter and spring; ↓ with depth in fall, ↑ with depth in spring
			Soil degree days—treatment, season	Burn plots ↑ fall and spring; ↑ with depth fall and winter, ↓ with depth spring and summer
			Soil degree days—microsite effects	Interaction of phase and microsite significant for soil temperature most seasons and years
			Spring soil wet—degree days	Phase 1 treated ↓ from 100 to 0 over years 1–4 posttreatment; Phase 2 ↓ 300–125; Phase 3 ↓ 400–225
			Spring soil wet days—phase effects	Phase 1 treated ↓ from 6 to 0 over years 1–4; Phase 2 ↓ 20–8; Phase 3 ↓ 26–18
			Spring soil wet days—site variation	Among-site variation ↑ at posttreatment year 2 compared to year 4
Pierson et al. 2014	WY–PJ, MT–PJ	1 year	Runoff/erosion—fire effects	Two similarly degraded sites varied markedly in response to high intensity rainfall
			Runoff/erosion—mastication effects	↓ Runoff/erosion four- to five-fold within interspaces at more erodible site
			Soil water repellency	Effects on infiltration exacerbated by fire removal of surface-protecting litter
			Soil aggregate stability	Indices not well correlated with runoff and erosion effects
Rau et al. 2014	WY–Shrub	2 yr	Resistance and soil texture	Sites with clay soils had ↑ resistance after treatment; sites with sand soils had ↓ resistance
			Exchangeable anions/cations	Increases greatest with fire and imazapic
			Perennial vs. exotic annual grasses	Perennials favored when precipitation and soil water ↑; annuals favored with ↑ phosphorus & gaps
Pyke et al. 2014	WY–shrub	3–4 yr	Perennial tall grass cover	↓ With fire year 1
			Cheatgrass cover	↑ With all treatments year 3
			Sandberg cover	↓ With fire through year 3
			Biological crust cover	↓ With fire and mow through year 3
			Bare soil cover	↑ With fire through year 3
			Cheatgrass—imazapic	↓ Combined with all treatments through year 3
			Annual forb—Imazapic	↓ Combined with all treatments through year 2
			Sandberg—imazapic	Initial ↓ combined with all treatments
			Perennial tall grass—imazapic	Initial slight ↓ combined with all treatments

Table 2. Continued.

Senior author	Ecological site[1]	Years after treat	Variables	Results
Chambers et al. 2014a	WY–shrub, WY–PJ, MT–PJ	3–4 yr	Shrub cover	No ↑ after treatment WY–shrub; ↑ WY–PJ and MT–PJ
			Native perennial herbaceous cover	↑ all site types; but treatment plots same as control WY–shrub
			Grass species with greatest response	WY–shrub: Sandberg, squirreltail; WY–PJ: bluebunch; MT–PJ: Idaho fescue
			Cheatgrass cover	↑ WY–shrub all treaments;↑ WY–PJ with fire;↑ MT–PJ with fire
			Annual exotic forb cover	↑ With treatments, especially fire
			Treatment severity	↑ With fire and with high initial tree cover
			Resilience to fire	↓ High tree cover plots
			Resilience	WY–shrub < WY—PJ < MT–PJ
			Resistance to cheatgrass	WY–shrub < WY–PJ, MT–PJ, with response related to soil temperature/moisture
Miller et al. 2014	WY–PJ, MT–PJ	3 yr	Bare ground cover	↑ Initially with fire, then return to pre year 3; no change with mechanical treatment
			Biological crust cover	↓ To 1/6 with fire year 3; ↓ to 2/5 with mechanical treatment year 3
			Shrub cover	↓ To 1/10 with fire year 1, rebound to 1/4 year3; no change with mechanical treatment
			Tall perennial grass cover	↓ Year 1 with fire, then ↑ to 1.2× year 3; mechanical treatment ↑ to 1.5× years 2 and 3
			Perennial forb cover	↑ To 2× year3 for fire and mechanical treatment
			Sage-grouse forb cover	↑ To 3× for fire, 2× for mechanical treatment
			Exotic cover (primarily cheatgrass)	↑ To 4× with fire year 3; ↑ to 3× with mechanical treatment year 3
			Litter cover	↓ Slightly with fire by year 3; ↑ slightly with mechanical treatment by year 3
			Shrub density	↓ With fire to 1/6 year 1, then rebound to 1/3 by year 3; no change with mechanical treatment
			Sagebrush seedling density	↑ With fire by year 3; ↑ with mechanical treatment by year 2
			Tall perennial grass density	No change fire or mechanical treatment
			Perennial forb density	No change fire or mechanical treatment
Roundy et al. 2014b	WY–PJ, MT–PJ	3 yr	Perennial tall grass cover	↑ Proportionally more at higher pretreatment tree cover
			Shrub cover	↓ With fire to near 0; ↑ with mechanical treatment across tree cover gradient
			Perennial shortgrass cover	No posttreatment difference among treatments at high pretreatment tree cover
			Perennial forb cover	Fire and mechanically treated plots rebound in high pretreatment tree cover plots
			Perennial herbaceous cover	Fire and mechanically treated plots rebound in high pretreatment tree cover plots
			Cheatgrass cover	↑ Proportional to pretreatment tree cover in fire and mechanically treated plots
			Cheatgrass vs. perennial herb cover	No relation in controls; negative correlation in fire and mechanically treated plots at SC and ST sites
			Cheatgrass/perennial herb ratio	↑ Exponentially with all treatments when tree dominance index > 0.85
Knick et al. 2014	WY–PJ, MT–PJ	3–4 yr	Passerine bird species composition	Woodland species ↓ with fire, no change in sage species
			Sage-obligate bird community	Most results subtle; Onaqui shred adjacent to sagebrush landscape used by sage-obligates

Table 2. Continued.

Senior author	Ecological site[1]	Years after treat	Variables	Results
McIver and Macke 2014	WY–shrub, WY–PJ, MT–PJ	4 yr	Butterfly vs. Veg Communities	Significant correspondence between floral and faunal communities across network
			Transient richness, abundance	Fire and mechanical treatments ↑ through 4 yr posttreatment
	WY–PJ, MT–PJ	4 yr	Abundance sulfurs	Fire and mechanical treatments ↑ through 4 yr posttreatment
			Abundance transient whites	Fire and mechanical treatments ↑ through 3 yr posttreatment
			Abundance juniper hairstreak	Fire and mechanical treatments ↓ through 4 yr posttreatment
			Abundance melissa blues	Fire, mechanical treatments ↑ through 3 yr posttreatment; response correlated with *Astragalus* host plant
	WY–shrub	4 yr	Abundance local butterfly	Fire and mechanical treatments ↑ through 4 yr posttreatment
Hulet et al. 2014	WY–PJ, MT–PJ	Not Applicable	Tree cover and biomass	NAIP data can estimate tree cover/biomass with 5% accuracy
				NAIP can reduce cost of monitoring tree cover/ biomass
Gordon et al. 2014	Sagebrush steppe	Not Applicable	Awareness of issues	People are becoming more aware of key threats facing sagebrush steppe lands
			Acceptance of treatments	Moderate for burning and most mechical treatments; lower for chaining and herbicides
			Trust vs. knowledge	Trust more important than knowledge in attaining public support for restoration
			Trust in federal agencies	Relatively low but generally higher in 2010 compared to 2006
			Willingness to get involved	Slightly higher in 2010 compared to 2006
Taylor et al. 2013	Sagebrush steppe	Not Applicable	Treatment economic efficacy	Restoration pays in reduced suppression costs only when ecosystems are healthy
			Uncertainty	Uncertainty regarding restoration outcomes lowers expected economic benefits
			Fire return intervals	Shortening of fire return intervals leads to large increases in fire suppression costs

[1] WY indicates xxx; PJ, piñon–juniper; MT, xxx; BC, Bridge Creek; ST, Stansbury; SC, Scipio; DR, Devine Ridge; WB, Walker Butte; BM, Blue Mountain; OJ, Onaqui Mountain; GB, Greenville Bench; SR, South Ruby; MC, Marking Corral; SV, Seven Mile; and NAIP, National Agricultural Imagery Program.

(Reisner et al. 2013). First, preferential grazing of bunchgrasses can increase the size of gaps between perennial plants, and thus encourage cheatgrass invasion into gaps. Second, intense grazing over time can result in the distribution of the largest bunchgrass individuals underneath sagebrush canopies. When these burn, it may result in higher heat pulses into the soil, thus killing bunchgrass individuals outright. These results suggest that SageSTEP results are more applicable to systems that are managed appropriately with respect to grazing.

In the long run, as long as a site has an adequate population of perennial bunchgrasses (typically $>10\%$ cover), treatment to reduce woody vegetation may result in higher resilience and resistance for most sites, to the extent that perennials have a greater capacity to survive drought years, and to therefore gradually increase their dominance of a site. Obviously, long-term data are needed to test this idea, at least to the point in time where excess water, released by woody vegetation reduction, is completely captured by surviving shrub and herbaceous vegetation (Roundy et al. 2014b).

Vegetation results must be placed within the context of issues of soil erosion and loss, particularly in sagebrush ecosystems that have been encroached by trees for a long period of time. SageSTEP hydrological work shows that when bare ground exceeds 50–60% on a given hillslope, both runoff and erosion increase precipitously (Pierson et al. 2013). If this percentage of bare ground has persisted for a long period of time, substantial fine sediment is removed and cross-scale erosion (e.g., patch to intercanopy to hillslope) takes place, thus inhibiting future plant growth, even when trees are removed. Thus degradation can reach a stage where resilience is very low, even at sagebrush sites that are both cool and moist. On the other hand, if disturbance occurs early enough in the tree encroachment process, before cross-scale erosion has removed most fine sediment from a hillslope, vegetation recovery can return a site

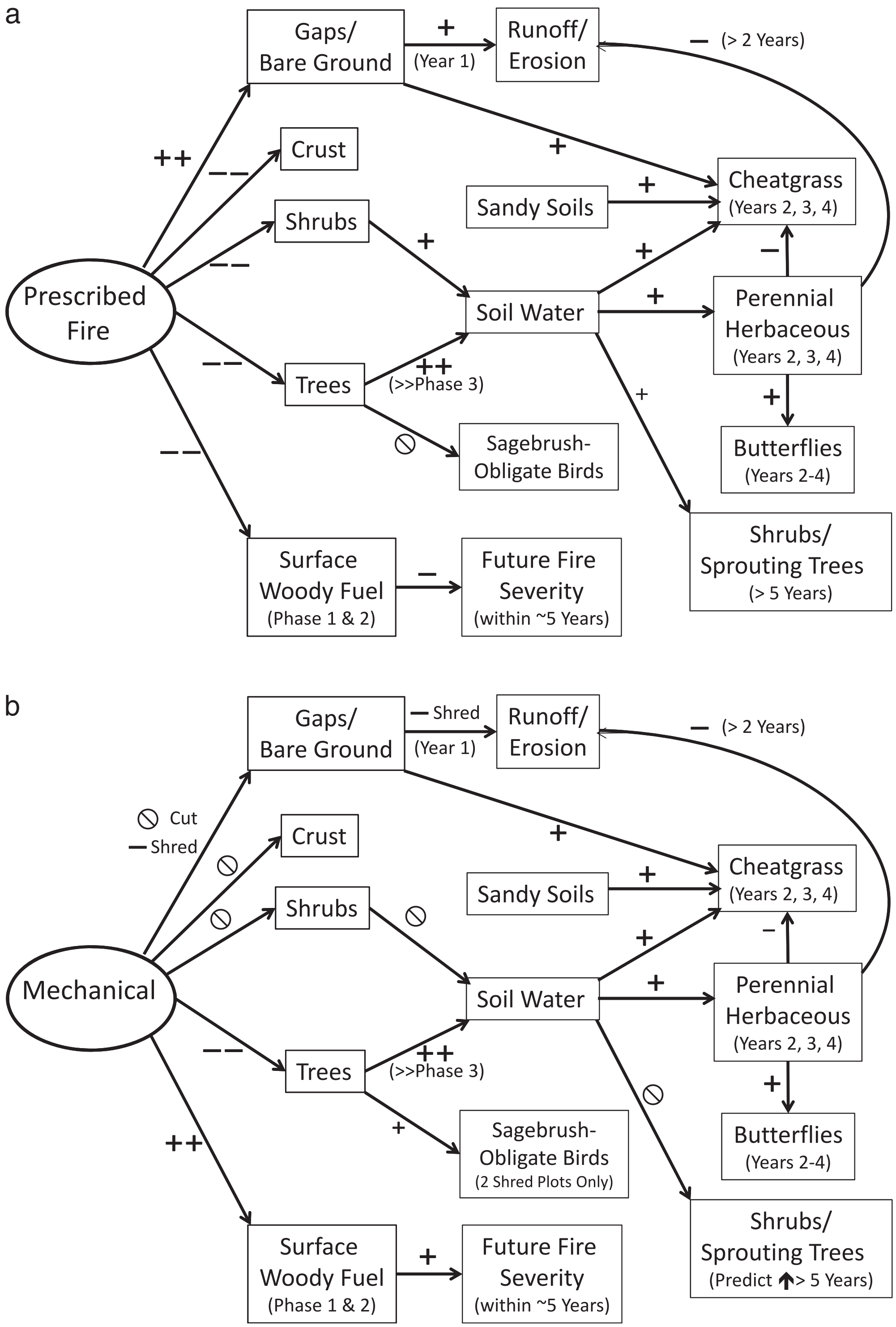

Figure 2. Conceptual models for short-term effects of **a,** prescribed fire and **b,** mechanical treatments for sage–cheat and woodland experiments, and inferred interactions among variables. Effects and interactions represent averages among sites (see Table 2 for details). ++ indicates increase > 3× relative to control; +, significant increase relative to control; ⊘, no significant effect; –, significant decrease relative to control; and ––, decrease < 1/3 relative to control.

to control by biotic processes and prevent it from shifting to an abiotically controlled system (Williams et al. 2014).

For the fauna, butterflies can be expected to generally track changes in the vegetation community (McIver and Macke 2014; Fig. 2). However, the response of the bird community to vegetation treatments is a more complicated picture of the interaction between the intensity and location of treatment (Knick et al. 2014). Prescribed fire, as applied in our treatments, was not effective at removing all trees from plots and between 6% and 24% cover of piñon–juniper still remained. Sagebrush-obligate birds have not been observed at those treatment locations, even after 5 yr posttreatment (Knick et al. 2014). The only treatments that successfully resulted in colonization by sagebrush birds occurred at two mastication plots at the Onaqui site (Fig. 2), where trees were completely removed at locations adjacent to an existing sagebrush expanse, which effectively increased the extent of the sagebrush landscape. Sagebrush birds began using these sites the year following treatment (Knick et al. 2014). These results demonstrate that restoration success, defined in terms of resilience and resistance, will likely depend on which component of the ecosystem one is considering. For vegetation, hydrology, and the native insect fauna, restoration success may be achieved at relatively small scales, and after relatively lower-intensity disturbances. For sagebrush-obligate birds, more intense disturbances located adjacent to an existing sagebrush landscape may be required to achieve a functioning sagebrush steppe ecosystem.

When land managers apply treatments to stands or landscapes, the goal is often to restore lands to a perceived fundamental structure or composition. In sagebrush steppe systems, this goal will be reached if native perennial vegetation responds well to treatment relative to annual exotic vegetation (Pellant 2007). We found that cool wet sites were generally more resilient after treatment than warm dry sites, and that resistance was mostly dependent on pretreatment cover of cheatgrass. In the short term, fire was more problematic than mechanical treatments because of initial cover decline in shrubs and bunchgrasses, which increased gap sizes and allowed cheatgrass to increase relative to perennials (Table 2). We also found that it will always be important to define resilience with a specific resource value in mind: sites that are resilient from the vegetation point of view may not be so from an avian point of view, due to differences in what constitutes a “restored” landscape. Site history will also be critical in predicting outcome of restoration treatments: hillslopes that have experienced many years in an encroached state may become so hydrologically degraded that they may not recover even after tree removal. Finally, we predict that additional time will alter outcomes on some sites, and that at least 10 yr will be necessary to judge restoration success on the majority of SageSTEP sites.

Fire vs. Fire Surrogates

For some components of the ecosystem, mowing, cutting, and mastication can serve as surrogates for prescribed fire, if both fire and fire surrogate treatments alter vegetation structure and resources in similar ways. For example, perennial forb cover (Miller et al. 2014) increased to a similar degree after both fire and mechanical treatments, probably due to enhanced soil water availability as a consequence of tree removal by any means (Roundy et al. 2014b; Table 2). Local butterfly abundance tracked vegetation changes, probably due to enhanced floral resources associated with the increase in overall forb cover (McIver and Macke 2014; Fig. 2).

Yet fire is well known to have unique effects on ecosystems that cannot be emulated by any other management action (DeBano et al. 1998). As expected, shrub cover was reduced much more by prescribed fire than by any other kind of treatment (Miller et al. 2014; Pyke et al. 2014). Bare ground also increased more after prescribed fire than by mechanical or herbicide treatments (Miller et al. 2014), and the combination of shrub and bare ground effects made prescribed fire the most ecologically severe treatment (Chambers et al. 2014a). In addition, although mastication was as effective as fire in removing trees and altering the fuel bed, the accumulation of shredded material on the ground surface created radically different hydrological and fire behavior conditions, compared to prescribed fire (Fig. 2a vs. 2b). Runoff was impeded by shredded debris, which served to reduce erosion (Cline et al. 2010), whereas prescribed fire increased the percentage of bare ground, which increased both runoff and erosion. Yet prescribed fire was the only treatment that reduced fire severity during the Big Pole wildfire, which burned through the Stansbury site 2 yr after treatment (B. Roundy, unpublished data). This emphasizes the point that in order to decrease future fire severity one must remove fuel from a site, either through prescribed fire, or through cut-and-remove treatments. Fire also had more marked effects on gap size (Pyke et al. 2014) and the availability of exchangeable nutrients and soil water in the sage–cheat experiment, especially when combined with imazapic (Rau et al. 2014). One important consequence of these belowground and ground cover differences is that fire will generally tend to reduce resistance to cheatgrass invasion on warm dry sites, at least in the short term (Miller et al. 2014). Finally, for the bird community, mechanical treatments that completely removed the tree cover, retained the sagebrush component, and were located adjacent to an existing sagebrush landscape were more effective than prescribed fire (Knick et al. 2014) in creating habitat for sagebrush-obligate birds.

With the exception of increased water availability (Roundy et al. 2014b), mechanical treatments did not serve as surrogates for prescribed fire (Table 2). The distinct differences in how alternative restoration treatments function on the landscape present opportunities for managers to select different tools for particular purposes, especially given the fact that the public will generally accept the types of treatments studied by SageSTEP (Shindler et al. 2011; Gordon et al. 2014), if circumstances are believed to warrant it.

Trade-Offs

The multivariate design of SageSTEP, in which several key variables were measured simultaneously in the same study plots, allowed us to assess potential trade-offs that managers may want to consider when choosing among alternative restoration strategies. In the most basic sense, there will always be trade-offs in that some species will decline and some will increase, no matter what managers do on the landscape. For example, tree removal clearly decreased the abundance of hairstreak butterflies (*Callophrys gryneus)*, because larvae of this species depend on juniper to grow and mature (McIver and Macke 2014). Similarly, woodland ecotone birds such as green-tailed towhees (*Pipilo chlorurus*), chipping sparrows (*Spizella passerina*), and gray flycatchers (*Empidonax wrightii*) declined in abundance due to the loss of the trees they use for nesting and foraging (Knick 2012).

There are also trade-offs regarding short- vs. long-term considerations. Although prescribed fire leads to increases in native perennial bunchgrass cover in the intermediate term, fire also reduced cover of both shrubs and biological crusts, and by 3 yr posttreatment, neither had recovered to near pretreatment levels (Table 2). In fact, it may take 10–15 yr or longer for shrubs to recover, and up to 20–30 yr for biological crusts to recover at most sites (Miller et al. 2014). Likewise, imazapic clearly reduced cheatgrass cover in the short term, which may at some sites have created an opportunity for native perennial bunchgrasses to dominate in the years to come. Yet some species of native annual forbs were also impacted by imazapic in the short term, as well as the shallow-rooted native perennial Sandberg bluegrass (*Poa secunda*; Pyke et al. 2014). How should we weigh these short-term benefits and losses in the context of longer-term benefits that may occur if treatment gives native perennial bunchgrasses a better chance of claiming and ultimately dominating a site? Similarly, prescribed fire on hillslopes of encroached woodlands caused a sharp increase in runoff in the short term, especially within the coppices formerly occupied by trees (Pierson et al. 2013). Yet, leaving the trees in place renders the interspaces between trees vulnerable to loss of surface soil, which may eventually lead to the crossing of an irreversible threshold (Pierson et al. 2010; Williams et al. 2014). Leaving trees remaining in the vegetation community, either by design or because of an incomplete treatment, also resulted in a landscape that was unsuitable for use by sagebrush-obligate birds (Knick et al. 2014). Mastication is clearly an effective alternative technique for removing trees, because the shredded material protects the hillslope from runoff in both coppices and interspaces (Cline et al. 2010; Pierson et al. 2014). But placing so much shredded material on the ground surface increases risk of severe effects should a wildfire occur in the near to intermediate future (B. Roundy, personal communication). In fact, prescribed fire is the only tree removal treatment that has the capacity to reduce potential fire severity, because it is the only treatment that efficiently reduces on-site surface fuel loadings (Bourne and Bunting 2011).

Trade-offs may also be evaluated in terms of their economic, social, or political implications. An economic simulation based on SageSTEP data suggested that fuel treatment is economically efficient only when the two ecosystems are in relatively good ecological health—i.e., before cheatgrass becomes dominant (Taylor et al. 2013; Weltz et al. 2014). However, those calculations compare the cost of treatments to the potential costs averted by not having to suppress a future wildfire. There may be circumstances in which managers determine it is worthwhile for ecological reasons to treat an invaded site in an effort to increase resilience to fire, even if the economic equation doesn't come out in favor of treatment. Similarly, because herbicide application is the least socially acceptable treatment (Shindler et al. 2011; Gordon et al. 2014), managers may opt against applying imazapic as part of a restoration treatment in an especially sensitive location, even though doing so could have benefits for suppressing reinvasion by cheatgrass. Acceptance of treatment options depends not only on public perceptions of trade-offs between ecosystem health and risks to rangeland values, but even more so on their trust in land managers to apply the treatments safely and effectively (Gordon et al. 2014). Investment in activities that build and/or maintain trust (Shindler et al. 2014) can afford managers opportunities to employ all the tools in the management toolbox without opposition.

There are obviously many other potential trade-offs with which managers must contend. In fact, trade-offs are inevitable whenever managers attempt to manage a complex natural system, and their existence underlines the importance of asking the right questions about the *whole system* when developing objectives for management treatments (Miller et al. 2007).

Temporal Scale

Reduction of woody vegetation represented a "shock" to the system each time a treatment was applied to a plot. This shock can be envisioned as a wave with magnitude and duration that differed for each variable measured. The target variables—those that treatments were intended to modify—include the fuel bed and woody vegetation cover, and these were influenced immediately after treatment in 2006, 2007, and 2008.

Although treatment implementation was successful for most prescribed fire and all mechanically treated plots in the study, the vegetation successional trajectories and resulting changes in fuels remain to be seen. Measurements taken 3 yr after treatment show only modest shrub cover rebound, primarily due to the fact that major cover increases could require recolonization of treated sites, a process that may require decades (Table 2). While some sprouting of Utah juniper is already occurring at some sites, even more time would be required for tree cover to return to pretreatment levels (Roundy et al. 2014a). Thresholds in response to recovery of the tree component also varied among the system's components. For example, low densities of tree cover and low height that otherwise have little influence over soil, vegetation, and hydrological processes can be important features that cause avoidance by sagebrush-obligate birds. We would expect other components of the fuel bed to change in more complicated ways, depending on treatment, with changes in masticated fuel beds dependent on 100-h fuel decay rates, and changes in prescribed burned fuel beds dependent on snag deterioration and fall rates.

Reduction of trees and/or shrubs caused an increase in soil water (Roundy et al. 2014b) and nutrients (Rau et al. 2014) that became useable by herbaceous vegetation (Miller et al. 2014) once conditions became warm enough in the spring following treatment (Roundy et al. 2014a; Fig. 2). This immediate boost in herbaceous production was due in part to increases in perennial forb cover, but mostly to growth of preexisting perennial grasses (not recruitment of new individuals). Herbaceous cover increase occurred more quickly in mechanically treated plots (first spring after treatment), and was still ongoing in all treated plots the third spring after treatment (Miller et al. 2014; Pyke et al. 2014). Interestingly, cover of exotics in the woodland experiment declined in the first year after all treatments, but then rebounded to higher than pretreatment levels, especially with fire, in years 2 and 3 (Miller et al. 2014). Cheatgrass cover similarly declined initially in the sage–cheat experiment, but then rebounded by years 2 and 3, especially with fire (Pyke et al. 2014; Table 2). In woodlands, shrub cover was unchanged by mechanical treatment, was reduced by fire immediately to about 10% of pretreatment levels, and had recovered by the third spring to 25% of pretreatment levels (Miller et al. 2014). In treeless sagebrush steppe, shrub cover was reduced immediately by fire to $<25\%$ pretreatment, and had recovered only slightly by the third spring after treatment (Pyke et al. 2014). While the initial increase in availability of nutrients after treatment will likely disappear by 4 yr posttreatment (Rau et al. 2014), additional soil water may continue to be available in Phase 2 and 3 woodlands for many years posttreatment (Roundy et al. 2014b). Because both native perennials and annual exotics were still increasing at year 3 posttreatment, it remains to be seen which functional groups will hold the upper hand, and at which sites, when all the additional soil water made available by treatment has been appropriated. In terms of runoff and erosion, the rapidity of response of the herbaceous vegetation will in turn be the key to recovery of more desirable hydrological function in burned plots. Two years after prescribed fire, erosion in intercanopy areas had already declined due to enhanced herbaceous production, which impeded overland flow (Pierson et al. 2013; Williams et al. 2014). Longer-term impacts on runoff and erosion will depend on persistence of enhanced intercanopy vegetation and how effectively vegetation occupies former tree coppices (Pierson et al. 2007). We predict that measurements taken in 2015 (9 yr posttreatment) will show a precipitous decline in runoff and erosion across all burned plots.

The influence of treatment on bird communities may take >15 yr to fully express, for two primary reasons. First, birds respond indirectly to treatment through changes in the relative abundance of plant functional groups, including trees and shrubs. The stability of these functional groups likely will take many years to develop. Second, the bird community has an inherent lag period in response because adult birds often express site fidelity to places where they have formerly nested or been hatched. Hence, these birds may return to treated areas even if the vegetation composition and structure no longer are suitable for brood-rearing. Thus a more meaningful test of treatment effects may require the assessment of how future generations respond to treated areas, and this may take >15 yr. In any case, plans to remeasure SageSTEP plots in 2016–2018 should reveal much about how the many components of these systems ultimately respond to treatment applied 10 yr before.

Woody vegetation reduction initiated a cascade of effects on treated sagebrush steppe plots, beginning with increases in the availability of nitrogen and soil water by the spring following treatment (Fig. 2). Increased growth of herbaceous vegetation followed, including annuals and perennials of both grasses and forbs. The response of butterflies and magnitudes of runoff and erosion closely followed herbaceous vegetation recovery, demonstrating the short-term importance of grasses and forbs in this ecosystem. Other variables, such as shrub, biological soil crust, tree cover, surface fuel loads, and sagebrush-obligate bird communities, will likely take many years to fully express, demonstrating the importance of long-term monitoring of restoration treatments.

Heterogeneity

Sagebrush steppe ecosystems vary considerably among ecoregions and over environmental gradients within the geographic area represented by SageSTEP (Chambers et al. 2014b). The study was therefore designed as two multisite experiments in an effort to understand how different inherent conditions might influence treatment response. Although SageSTEP scientists knew that 20 sagebrush steppe study sites could not possibly cover the full range of possibilities, they have been surprised by the magnitude of both spatial and temporal heterogeneity, both pretreatment and posttreatment. Spatially, each site in both studies is clearly unique, even when located close to one another. The two Hart Mountain sage–cheat sites are located less than 3 km apart, and while they are floristically more similar to one another than to the other five sage–cheat sites, in soils, vegetation, and butterflies, they are unique and easily distinguished (McIver and Macke 2014; Pyke et al. 2014; Rau et al. 2014). Spatial heterogeneity was also evident among plots within sites for nearly every site in the study. The avian study site at Five Creeks consisted of paired control and burned 1 000-ha plots that were distinctly different from one another in bird community structure prior to treatment (Knick 2012). At the western juniper Walker Butte site, the three study plots are arranged linearly and adjacent to one another, and yet pretreatment flora ordinated in three distinct groups: the control plot featured higher mean gap size and cover, the mechanical plot had higher big sagebrush and annual forb cover, and both the prescribed burn and mechanical plots had higher perennial grass cover. These differences ramified throughout the system, as shown in butterflies, which are dependent on the native flora for larval food resource (McIver and Macke 2014). Thus, posttreatment surveys of butterflies reflect both the preexisting and persistent floral differences among plots and the influence of the treatments applied to them. Temporal heterogeneity, especially interannual variation in weather, further increased variation in treatment response. October through June precipitation varied by as much as two-fold at some woodland sites between 2006 and 2011, and the interaction of this variation with the three treatment years (2006, 2007, 2008) added further to the expression of temporal heterogeneity (Roundy et al. 2014b). The combination of both spatial (among sites) and temporal (among years) heterogeneity explains the wide error bars around mean treatment response in most of our analyses (Chambers et al. 2014a; McIver and Macke 2014; Pyke et al. 2014).

Substantial spatial and temporal heterogeneity accentuates the point that there will rarely ever be a “recipe” for choosing management actions on any specific area, no matter how much information is available. Yet SageSTEP has already identified several clear patterns of response in vegetation communities that have allowed us to develop state-and-transition models that include estimates of resilience and resistance for the major ecological types in sagebrush steppe lands (Chambers et al. 2014a). These state-and-transition models have now been incorporated into field guides (e.g., Miller et al. 2014), that are designed to help guide decision-makers through a process of landscape evaluation, like that emphasized in the western juniper “synthesis” (Miller et al. 2005), and original western juniper user’s guide (Miller et al. 2007). Certainly, managers’ use of a consistent evaluation process, linked to monitoring of key variables, represents a form of “adaptive management,” which may in the long run be their best chance for arresting the tide of encroachment and invasion that may accelerate in a future warming climate.

SageSTEP: WORTH THE EFFORT?

As one of the most ambitious research projects ever attempted in sagebrush steppe, SageSTEP has promised information of great value to land managers faced with the consequences of woodland expansion and cheatgrass invasion. Designed in collaboration with land managers, the two SageSTEP management experiments were intended to provide information based on long-term data, capable of identifying trade-offs and biological thresholds, and that compared alternative treatments across a wide range of ecological conditions. SageSTEP has now cost a little over $18 million (including both direct and contributed funds), and has occupied the time of several dozen scientists, technicians, students, and managers over its 10-yr lifespan. Has SageSTEP delivered on its promise?

The study has been and continues to be productive, having delivered hundreds of outreach products and activities, as well as 72 technical papers, including 37 in peer-reviewed journals, five doctoral dissertations, and six master's theses (sagestep.org). While nearly all of this information has been focused on the central issues of woodland expansion and cheatgrass invasion, the best measure of the study's efficacy is whether or not managers will find the information more useful than the more typical kind of information scientists have offered in the past (i.e., single site, few variables, short-term, etc.). How important is SageSTEP information, presented in the context of key site differences or invasion gradients, and offered in a multivariate form that emphasizes whole ecosystem response? At this point, the jury is still out. First, insufficient time has elapsed for evaluation of how information is being used, especially since our results are still very comparable to other short-term studies. More importantly, SageSTEP datasets are so rich that only a subset of potential analyses has so far been accomplished. Most analyses have been focused on only a handful of available variables, and in some cases for only a subset of available sites. Next on the horizon are comprehensive and integrative analyses that take advantage of a dataset that will soon consist of 6 yr of posttreatment data from all sites. While SageSTEP scientists are now poised to undertake these analyses, they would also welcome other investigators who have the interest and the tools to use this incomparably rich dataset for answering key questions on the ecology and management of sagebrush steppe ecosystems. Finally, management practices change over time, and so any long-term study may end up evaluating management treatments that become obsolete. Thus, judging the efficacy of a study based on whether or not management practices change in response to it may represent an unfair standard. Ultimately, a better indication of the value of studies like SageSTEP would be how the rate of basic knowledge gained compares to a scenario where research investment was spread out among many smaller, disarticulated studies.

MANAGEMENT IMPLICATIONS

Four years have now elapsed since treatments were applied at 21 SageSTEP sites, and initial results are very informative. At the warmest, driest Wyoming big sagebrush sites, prescribed fire will likely result in undesirable pulses of cheatgrass and exotic annual forbs in the short term, and application of imazapic will be unlikely to provide a window of opportunity for native perennial bunchgrasses to recover on invaded sites. At cool, moist sites, treatments likely will result in more desirable outcomes because these sites are more resistant to annual invasive species and resilient to management treatments. For sites in between these two extremes, responses have been intermediate and will likely be better defined with additional years of measurement.

Data on treatment response for a wide variety of variables has demonstrated that the native perennial herbaceous community represents the ecological lynchpin of sagebrush steppe ecosystems. Not only is the composition of the perennial herbaceous community important, but also how it is structured in relation to gaps and the remaining shrubs. If land managers focus on the recovery and sustainability of perennial native grasses and forbs, both the resilience and resistance of these ecosystems should be increased. Yet for some components of the ecological community, especially those that operate at larger scales, restoration success must include other key attributes. For example, while a prescribed fire treatment that removes 80% of the tree cover at a site may be judged a success from the perspective of fuels, vegetation, butterflies, or hydrology, the continued presence of *any* trees, dead or alive, will preclude the site from being judged a success from a sagebrush-obligate bird perspective. More than anything else, SageSTEP work has underlined the need to think about sagebrush steppe systems on multiple spatial and temporal scales, and with different values in mind. Not only do factors such as soil, microclimate, and invasibility influence decisions, but so do social and economic costs and benefits. A "fuel reduction" treatment therefore, becomes much more than a means to alter the fuel bed—rather, the treatment is a tool that can be used to alter environmental conditions that in turn drive hydrological and vegetation response, and that in turn represent new habitat features for a wide variety of plant and animal species.

The multisite, multivariate, long-term design of SageSTEP has greatly increased our understanding of how restoration treatments function under a wide variety of circumstances, and we expect the study to provide ever more valuable information as more posttreatment time elapses. There is no denying that substantial among-site variation in key ecological attributes will likely always cloud our ability to predict specific outcomes for many sites. Interannual variation, especially in the availability of water in spring, blurs predictive ability further. Yet it is this same spatial and temporal variation that provides the structure within which these systems operate. Studies such as SageSTEP therefore represent a unique opportunity to gain significant insight into ecosystem processes and to develop a better foundational understanding of how sagebrush steppe systems respond to disturbance.

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