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Postfire shrub cover dynamics: A 70-year fire chronosequence in mountain big sagebrush communities☆

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ABSTRACT

Fire is natural in sagebrush (*Artemisia* L.) communities. In this study, we quantify effects of time since last burn (TSLB) on shrub cover over a 70-year (yr) fire chronosequence. We sampled mountain big sagebrush communities with very large-scale aerial (VLSA) imagery and measured sagebrush, antelope bitterbrush (*Purshia tridentata* [Pursh] DC.), and spineless horsebrush (*Tetradymia canescens* DC.) cover. We used segmented regression to describe two cover phases with respect to TSLB. Phase 1 was when cover responded to TSLB and Phase 2 was when cover had reached a steady state with respect to TSLB meaning that expected shrub cover did not change with increasing TSLB. In the first year after burning, total shrub cover was 5%. In Phase 1, total shrub, sagebrush, and bitterbrush cover increased with TSLB. Bitterbrush transitioned to Phase 2 in 6 yr, but 19 and 18 yr, respectively, were needed for sagebrush and total shrub to transition. Horsebrush cover decreased with TSLB from 2.1% to 0.2% over 27 yr. Steady-state cover for sagebrush, bitterbrush, and total shrub were 30.6, 2.8, and 39.8%, respectively. These data describe postfire shrub cover change in mountain big sagebrush communities that can be used in management plans that meet shrub cover objectives.

1. Introduction

Fire is a useful tool for managing woody species in shrubland ecosystems (Blaisdell, 1953; Harniss and Murray, 1973; Wright and Bailey, 1982; Cook et al., 1994; Miller and Rose, 1999; Bates et al., 2009; Beck et al., 2009). Scientists at the USDA-ARS, U.S. Sheep Experiment Station (USSES), near Dubois, ID, USA, began conducting research on the effects of fire in the sagebrush steppe on USSES lands in 1936 (for review see Seefeldt and Laycock, 2006). The USSES has continuous records of fire occurrence since that time. In 2006, burned locations (wildfire and planned) on the USSES headquarters property within the mountain big sagebrush communities range in time since last burned (TSLB) from 1 to >70 year (yr).

A challenge with characterizing change that occurs following a disturbance event and modeling these changes has been the tendency to want to define a recovered state that the community will return to in time. In cases of fire, investigators have often looked to adjacent unburned areas as representing the unburned (i.e. recovered) areas that the burned areas will be compared with to judge recovery. Long chronosequences with a common ecological site can be used to better characterize periods when the community is responding to the disturbance such as fire and when it has reached a period when the community has stopped responding to the disturbance and the disturbance is no longer a factor in determining any further changes in the community.

In addition to mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* [Rydb.] Beetle), antelope bitterbrush (*Purshia tridentata* [Pursh] DC.) and spineless horsebrush (*Tetradymia canescens* DC.) are shrubs that commonly occur on USSES properties. Both wildlife and livestock species utilize these shrubs for nutrition and cover. However, in the absence of fire forage production is decreased, and habitat quality for some wildlife use is decreased

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(Blaisdell, 1953; Harniss and Murray, 1973; Wright and Bailey, 1982; Cook et al., 1994; Miller and Rose, 1999; Bates et al., 2009; Beck et al., 2009). Mountain big sagebrush communities have a natural fire return interval of between 12 and 30 years (Miller and Rose, 1999). Although fire can be used to manage shrubs, it results in temporary absence of important food and cover species, such as sagebrush and bitterbrush (Crawford et al., 2004; Ferguson, 1968). Therefore, an understanding of shrub dynamics is important to land managers when they are considering using fire to meet management objectives for wildlife and livestock that are utilizing rangelands.

Each shrub species responds differently to burning and the rate at which cover increases depends on initial response to fire. For example, fire easily kills big sagebrush, and it does not resprout (Blaisdell, 1953). Increases in cover must come from germination, establishment, and survival of seedlings; thus, recruitment of new plants is usually episodic (Lommasson, 1948; Bunting et al., 1987; Booth, 2002). Depending on whether the ecotype resprouts, bitterbrush is either decimated by fire or returns relatively quickly (Blaisdell and Mueggler, 1956; Nord, 1965). Horsebrush is a transitory dominant of big sagebrush communities that increased rapidly after fire from resprouts (Yong and Evans, 1978). Because of these unique differences, land, wildlife, and livestock managers must consider shrub responses to fire when they are developing long-term management objectives that are focused on improving shrublands.

Wildlife and livestock will use shrubs for nutrition, reproduction activities, and(or) shelter. However, degree of livestock and wildlife success in shrubland ecosystems will vary with the transitions of shrub presence in response to fire. Although sheep will consume sagebrush, it typically makes up a small portion of their diet (Beck and Peek, 2005). Therefore, burning mountain big sagebrush dominated sites was used to increase total forage availability and palatability for livestock (Blaisdell, 1953; Bates et al., 2009). Recommended sagebrush canopy cover for successful sage grouse nesting is 15–25% (Connelly et al., 2000). However, absence of fire resulted in big sagebrush cover of >40% (Blaisdell, 1953). Antelope-bitterbrush resprouts in response to fire resulted in increased quality of available forage for grazing ungulates, and the increased quality compensated for reduced forage volume (Kituku et al., 1992). Bitterbrush also provided nesting cover for sage grouse (Crawford et al., 2004). Unlike bitterbrush, horsebrush can be toxic to grazing animals (James and Johnson, 1976; Whitson et al., 1996), and significant increases in horsebrush following a burn could negatively influence the forage quality of range. These examples of how postfire shrub responses may influence livestock and wildlife success in shrubland further demonstrates the need for data that can be used to make reliable forecasts of when shrubs will reach levels of cover that meets management objectives. Therefore, the objective for this study was to utilize a long (70 year) fire chronosequence to determine the postfire responses of bitterbrush, horsebrush, and sagebrush cover relative to time since last burn (TSLB), and to describe shrub response phases in a mountain big sagebrush community. Phase 1 is a period when shrub cover is changing with each year since the burn and Phase 2 is a period when expected shrub cover no longer increases or decreases as a result of more years since the burn.

2. Materials and methods

2.1. Site description

The study area was a 5380-ha area located at the USSES (southwest corner is 44.272° N, 112.189° W, 1690 m elevation and northeast corner is 44.318° N, 112.057° W, 1890 m elevation). From 1971 to 2000, mean annual precipitation for this area ranged between 366 mm at the lowest elevation in the southwest corner and 491 mm at the highest elevation in the northwest corner (PRISM Climate Group, 2009). Mean daily maximum temperature was −2.8C in January and 28.4C in July for the southwest corner. Mean daily maximum temperatures were 0.8 and 1.7C cooler for January and July, respectively, for the northwest corner. Mean daily minimum temperatures were −13.9C in January and 8.8C in July for the southwest corner and were 0.3 and 0.8C cooler for January and July, respectively, for the northwest corner (PRISM Climate Group, 2009).

Within the study area, all sampling was confined to four soil-map units that were associated with ecological sites that had mountain big sagebrush as the dominant shrub species and bitterbrush as a subdominant shrub species. These soils occupied 4198 ha of the study area. The four map units were the Akbash–Maremma complex, 0 to 12 percent slopes; Maremma-Pyrenees-Akbash complex, 0 to 12 percent slopes; Maremma-Pyrenees-Akbash complex, 12 to 20 percent slopes; and Pyrenees–Maremma complex, 0 to 12 percent slopes (USDA-NRCS, 2006, unpublished report). Soils in the tentative Akbash series were deep and classified as Fine-loamy, mixed, superactive, frigid Calcic Pachic Argixerolls. Soils in the tentative Meremma series were very deep and classified as Fine-loamy, mixed, superactive, frigid Calcic Pachic Haploxerolls. Soils in the tentative Pyrenees series were moderately deep and classified as Loamy-skeletal, mixed, superactive, frigid Typic Calcixerolls (Soil Survey Staff, 2009).

Vegetation on the study area was a sagebrush-grass community, with mountain big sagebrush as the dominate shrub. Subdominant shrub species were antelope bitterbrush, yellow rabbitbrush (*Chrysothamnus viscidiflorus* [Hook.] Nutt.), threetip sagebrush (*A. tripartita* Rydb.), and spineless horsebrush. Dominant grass and grass-like species present were Sandberg bluegrass (*Poa secunda* J. Presl), bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] A. Löve), sedge (*Carex* L.), and Idaho fescue (*Festuca idahoensis* Elmer). Dominant forbs were parsnipflower buckwheat (*Eriogonum heracleoides* Nutt.), northwestern Indian paintbrush (*Castilleja angustifolia* [Nutt.] G. Don), longleaf fleabane (*Erigeron corymbosus* Nutt.), and littleleaf pussytoes (*Antennaria microphylla* Rydb.). Sheep annually grazed the study area in the spring and fall. Stocking rates were light to moderate, removing through grazing and trampling between 15 and 30 percent of annual production.

2.2. Fire chronosequence

Polygons for burns that occurred before 1995 were digitized in a geographic information system (GIS) from hand-drawn maps. From 1995 to the present, fire polygons were digitized using GPS receivers or satellite imagery. The 1995 and newer fire polygons excluded large unburned islands within fire boundaries, these either did not occur or were not mapped prior to 1995.

Over the 70-yr fire chronosequence, TSLB values were relatively well represented with small, typically less than 5-yr, gaps. The exceptions were a large 22-yr gap between 32 and 54 yr TSLB and a 9-yr gap between 16 and 25 yr TSLB. In 2006, approximately 22% of the sampling area had no history of fire since the start of 1936. The remainder of the sampling area had burned at least once, and some areas had burned as much as 5 times since 1936. Additionally, 20% of the sampling area was burned in a large wildfire in 1981. In 2006, the shortest TSLB was 1 yr.

2.3. Imagery

Very large-scale aerial (VLSA) imagery was used for shrub cover measurements. Color VLSA photographs were collected on the mornings of 16 and 17 June 2006, at an altitude of approximately 250 m above ground level (AGL). Planned image locations were spaced on a 300-m square grid over the entire USSES headquarters property. The aircraft was fitted with an 11-MP (4064 × 2704 pixels) camera, which was configured with a 100-mm focal-length lens, and a 16-MP (4992 × 3328 pixels) camera, which was configured with an 840-mm focal-length lens. The 16-MP images were used for shrub cover measurement. The 16-MP images had an average field of view (FOV) that was approximately 88 m^2 (11 × 8 m) based on aircraft-measured ground sample distance (GSD). The camera triggering system was electronically linked with the navigation system. The pilot maneuvered the aircraft along a planned flight path (within a lateral threshold), and the system triggered both cameras and logged the GPS position when it crossed the axial threshold for planned image locations. Laser altimeter data were logged with a time stamp so that the aircraft's altitude AGL at the time the cameras were triggered could be precisely determined. The altitude AGL was used to calculate pixel GSD for each image and adjust the image FOV. For a more complete description of the VLSA imaging system, see Booth and Cox (2006, 2008).

2.4. Sampling

Image acquisition locations were intersected with the soil map unit layer and the fire chronosequence layer in a GIS to classify each image with respect to soil map unit and time since last fire (Fig. 1). Median error between ground and aircraft reported image location was small (25.5 m) relative to the size of soil map units and fire chronosequence polygons (Moffet, 2009). Images that were not from one of the four selected soil map units, were not used in this analysis. TSLB values were not uniformly distributed along the

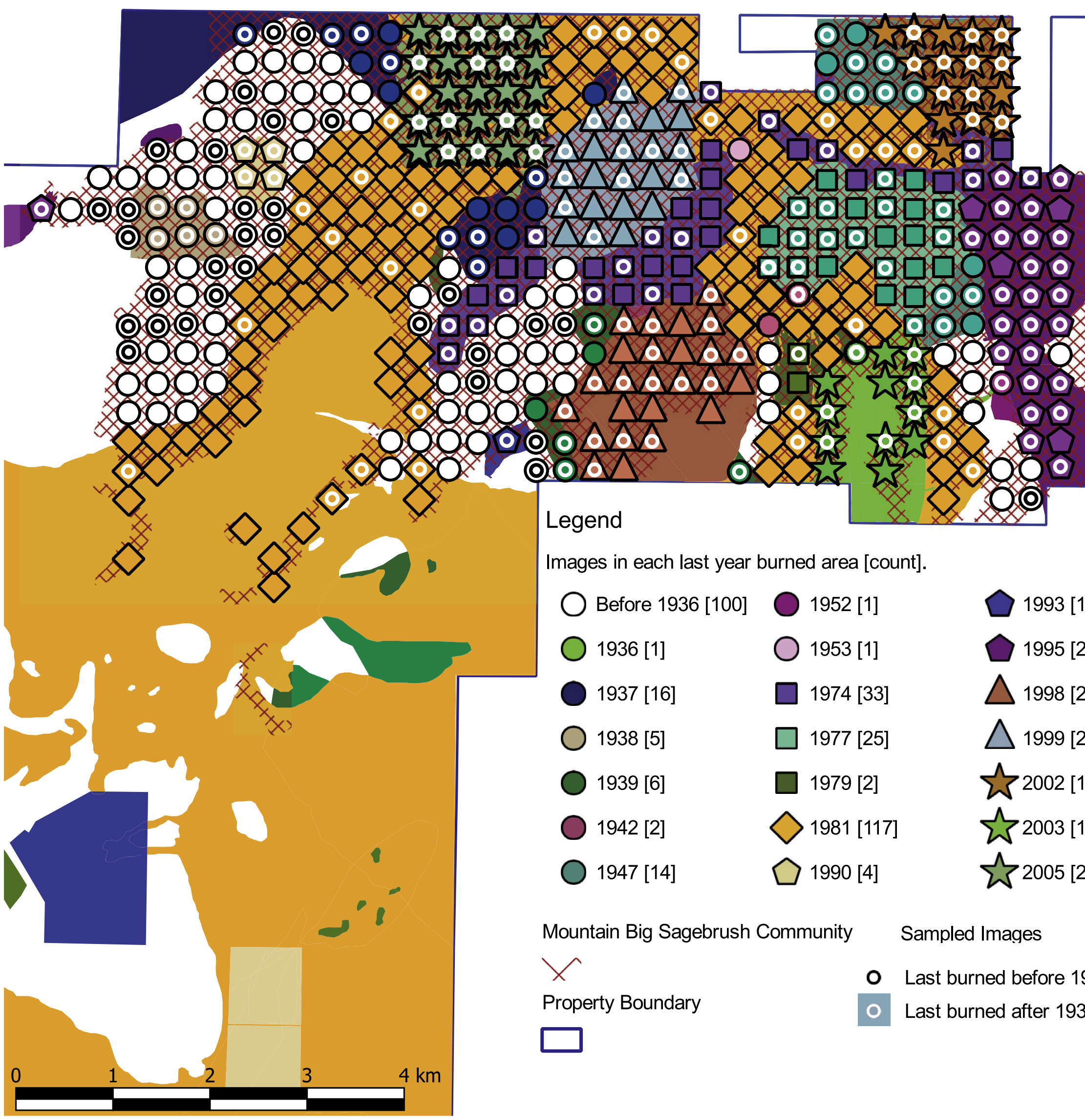

Fig. 1. Map of study area near Dubois, Idaho, USA showing 1) a portion of the USDA-ARS, U. S. Sheep Experiment Station headquarters property with soils that support mountain big sagebrush as the dominant shrub, 2) the fire history (i.e., last year burned) of the study area as of 2016 when imagery was collected, 3) the location 457 images classified according to last year burned, and 4) the 210 imagery locations that were sampled for shrub cover measurement. The solid-colored background shows the extent of each last year burned area as of 2006 (when the imagery was collected). In some cases, the image location symbol extends beyond its last year burned area boundary. The color scheme used is the same for the last year burned areas and the image location symbols. Sampled image locations were randomly selected from each TSLB class are indicated with an interior ring (before 1936 the rings are black and after 1936 the rings are white).

range of TSLB observed (see Table 1), so a stratified sampling regime was devised to get samples more evenly distributed along the observed range in TSLB. TSLB values were grouped into seven age strata to ensure that the entire range of TSLB was well represented by the sample. Starting with 1 yr TSLB, strata were defined to span at minimum of 5 yr and to include more than 30 images from which to sample. For each additional stratum, if there were not more than 30 image samples available in a 5 yr span, then years were added to the stratum until there were more than 30 images available. For example, the third stratum considered was 11–15 yr TSLB, but it only had 30 images available so another year was added to the stratum (i.e., 11–16 yr TSLB) and it had 34 images available. Further, the 17–21 yr TSLB stratum had no images available, so it was expanded to 17–25 yr TSLB before it had more than 30 images available. The 33–69 yr TSLB stratum, had 45 images available, but we choose to expand the stratum to 33–70 yr TSLB to include the one remaining image. There were 100 images available where TSLB was greater than 70 yr, and this constituted to >70 yr TSLB stratum. The resulting strata, named with the shortest to longest TSLB, included: 1 to 4, 7 to 8, 11 to 16, 25 to 25, 27 to 32, 54 to 70, and >70 yr TSLB. A computer generated pseudorandom sequence was used to select the 30 images from all available images within each stratum, for a total of 210 images. A classification error was discovered for one of the images from the 25 yr TSLB stratum (It should have been included in the >70 yr TSLB stratum). This was corrected, which explains the 29 samples from the 25 yr TSLB stratum and the 31 samples in the >70 yr TSLB stratum. For analysis, actual TSLB was used as the independent variable.

Table 1
Type of burn and season of burn for the area sampled. The images were sampled from areas grouped by stratum of similar (generally 5-yr intervals, but if a 5-yr interval had 30 or fewer images available, additional years were added to the stratum) time since last burn (TSLB). Image samples were drawn at random from each stratum. For a map showing the locations of the sampled images relative to available images and the year last burned areas available see Fig. 1.

Year last burned/Group (TSLB)	Images available	Images sampled	Type/season[a]
Before 1936 (>70)	100	31	NA
Before 1936 (>70)	100	31	
1936 (70)	1	1	P/S
1937 (69)	16	8	P/U
1938 (68)	5	5	W/U
1939 (67)	6	4	W/U
1942 (64)	2	1	W/U
1947 (59)	14	10	P/U
1952 (54)	1	1	P/U
1953 (53)	1	0	NA
1936 to 1952 (54–70)	46	30	
1974 (32)	33	16	W/U
1977 (29)	25	13	P/P
1979 (27)	2	1	P/S
1974 to 1979 (27–32)	60	30	
1981 (25)	117	29	2 P/P, 22 W/S, and 5 P/S
1981 (25)	117	29	
1990 (16)	4	4	P/P
1993 (13)	1	1	P/U
1995 (11)	29	25	P/F
1990–1995 (11–16)	34	30	
1998 (8)	25	17	P/S
1999 (7)	23	13	P/S
1998–1999 (7–8)	48	30	
2002 (4)	16	11	P/F
2003 (3)	12	6	P/F
2005 (1)	24	13	P/S
2002–2005 (1–4)	52	30	
Total	457	210	

[a] Type: P for prescribed or W for wildfire; Season: P for spring, S for summer, or F for fall.

ImageJ software (Rasband, 2006) was used for cover measurements. One-hundred pixels were selected at random from within each image for point intercept measurement; each pixel was classified into one of the following categories: sagebrush, bitterbrush, horsebrush, other shrub, not shrub, or unknown. Two computer generated pseudorandom sequences were used to select the coordinates for each sampled pixel. Mountain big sagebrush and threetip sagebrush could not be differentiated consistently in the imagery, so they were combined as sagebrush. Threetip sagebrush was, however, nonexistent in the majority of ground-validation samples (Moffet, 2009) and, in general, constitutes a small fraction of the sagebrush composition in these communities. Cover was measured as the proportion of sampled pixels from each class. In a previous validation study, where classical line-intercept measurements were made in the field on georeferenced plots and compared to point-intercept measurements in the imagery of the same area, the ground-based line-intercept and VLSA point-intercept cover measurements of sagebrush, bitterbrush, and total shrub cover were equivalent (Moffet, 2009). In the validation study, a limits-of-agreement approach was taken to compare methods. VLSA point-intercept measurements of sagebrush, bitterbrush, and total shrub cover were unbiased and agreement was similar to the repeatability of the ground-based measurements. VLSA point-intercept measurements of horsebrush cover were biased and underestimated the ground-based cover value by 1.2% when horsebrush cover, as measured on the ground, ranged from 0 to 11.9% (Moffet, 2009).

2.5. Statistical analysis

Regression was used to characterize the relationship between cover and TSLB. The data used to explore this relationship were the cover measurements and the TSLB for the 179 plots with known TSLB. The 31 plots where TSLB was only known to be greater than 70 years were used to approximate unburned areas. Four possible models were considered, as follows:

$$\widehat{Y}_i = \beta_0 \tag{1}$$

$$\widehat{Y}_i = \beta_0 + \beta_1 X_i \tag{2}$$

$$\widehat{Y}_i = \beta_0 + \beta_1 X_i + \beta_2 (X_i > \psi)\,(X_i - \psi) \tag{3}$$

$$\widehat{Y}_i = \beta_0 + \beta_1 (X_i \le \psi)\,(\psi - X_i) \tag{4}$$

where $\widehat{Y}_i$ is the cover estimate of the ith plot, X_i is the TSLB (yr) of the ith plot, β_j is the jth model parameter, ψ is the break-point, or threshold, TSLB (yr) when the annual rate of cover change was significantly different than before the threshold TSLB; the inequality terms evaluate to 1 if true and 0 otherwise. All models were fit using *R* statistical program (version 3.0.2, R Development Core Team, 2013). Models 1 and 2 were fit by the lm function and models 3 and 4 were fit by the segmented function in the segmented package (version 0.2–9.5, Muggeo, 2008; Muggeo, 2003). Model 1 is a simple mean cover model and assumes that cover is unrelated to TSLB and expected cover is constant over the entire 70-yr TSLB chronosequence. Model 2 assumes that cover changes in relation to TSLB and that the rate of change is constant across the 70-yr TSLB chronosequence. Model 2 is the standard linear regression of cover on TSLB. Model 3 assumes that cover changes in relation to TSLB, but that the rate of change depends on TSLB and allows for different rates of change in different regions of the 70-yr TSLB period. Model 4 assumes that cover changes in relation to TSLB, but only for a critical period of TSLB, beyond that critical time period cover does not respond to TSLB. Model 4 is a linear plateau model. Graphical analysis of the relationship between horsebrush and TSLB suggested that perhaps two breakpoints were needed in Phase 1 to allow for an initial period of increasing cover followed by a period of decreasing cover, but the method did not converge on unique breakpoints, and thus, only a single breakpoint model was considered. An F-test was used to compare the models, and, if the difference was not statistically significant ($\alpha = 0.05$), the simpler model was retained.

Distribution of errors from the resulting regression models were graphically evaluated to determine whether the errors were normally distributed, and the Breusch–Pagan test was used to test for constant error variance. In each case, errors from the raw data did not suggest that the assumptions were met and an arcsine-square root transformation was made for all response variables. These transformations resulted in improved error distributions. In general, errors were a slightly heavy-tailed, but they were symmetric and the variance was constant. All results are presented in back-transformed units of percent cover. We present break-point estimates plus and minus half the width of the 95% confidence interval.

3. Results

Overall, cover for all shrub species had 2 distinct response phases with respect to TSLB. In Phase 1, the dynamic phase, cover changed as a function of TSLB, but in Phase 2, the steady-state phase, cover is unrelated to TSLB. In each case, Model 4 best fit these data and this response pattern is a template for all shrub species reported in the current study (see Table 2).

Sagebrush cover was 0.1% in the fire year (Fig. 2). During Phase 1, sagebrush cover increased each year until it reached steady-state cover at 19 ± 1.9 (SE) yr TSLB. The arcsine-square root of cover increased linearly at 0.03 ± 0.004 (SE) units per year and sagebrush cover plateaued at 31%. In Phase 2, cover was not a function of TSLB

Table 2
Fit statistics for each cover type and each of 4 models evaluated to describe the relationships between the amount of cover provided by each type and TSLB. The models in bold font, Model 4 in all cover type cases, were selected to best describe these relationships. These models were chosen on the basis of lowest AIC and the principle of choosing the most parsimonious model between 2 models that do not differ significantly and lest parsimonious model only when significantly better according to the F-test.

Model	Error-df	RSS	Adjusted R-square	AIC
Sagebrush				
1	178	11.070	NA	13.8
2	177	7.237[a]	0.343	−60.3
3	175	4.710[a]	0.567	−133.2
4	**176**	**4.713**	**0.570**	**−135.1**
Horsebrush				
1	178	1.695	NA	−322.1
2	177	1.536[a]	0.089	−337.8
3	175	1.456[a]	0.127	−343.3
4	**176**	**1.469**	**0.124**	**−343.7**
Bitterbrush				
1	178	3.877	NA	−174.0
2	177	3.757[a]	0.025	−177.6
3	175	3.539[a]	0.072	−184.3
4	**176**	**3.552**	**0.074**	**−185.7**
Shrub				
1	178	8.658	NA	−30.2
2	177	5.999[a]	0.303	−93.9
3	175	4.535[a]	0.467	−139.9
4	**176**	**4.437**	**0.482**	**−145.8**

[a] The F-test comparing the current model with the preceding model is significant ($\alpha = 0.05$) indicating the current model is a better fit to the data than the preceding model.

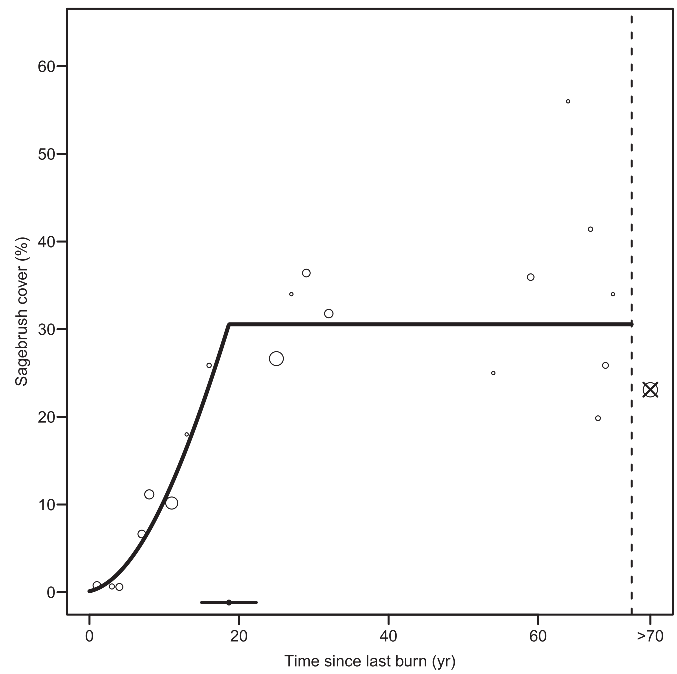

Fig. 2. Response of sagebrush cover to time since last burn (TSLB). Plot shows mean cover for each year (○; greater size of the symbol indicates more samples from that year; see Table 1 for the actual number of plots sampled in a given year) and mean of the >70-yr TSLB (⊗, $n = 31$); segmented relationship between year since last burn and percent sagebrush cover (solid curve); estimated threshold of TSLB when rates of change in cover change (•; displayed along the lower margin of the plot); and 95% confidence interval of the threshold (heavy solid line; displayed along the lower margin of the plot).

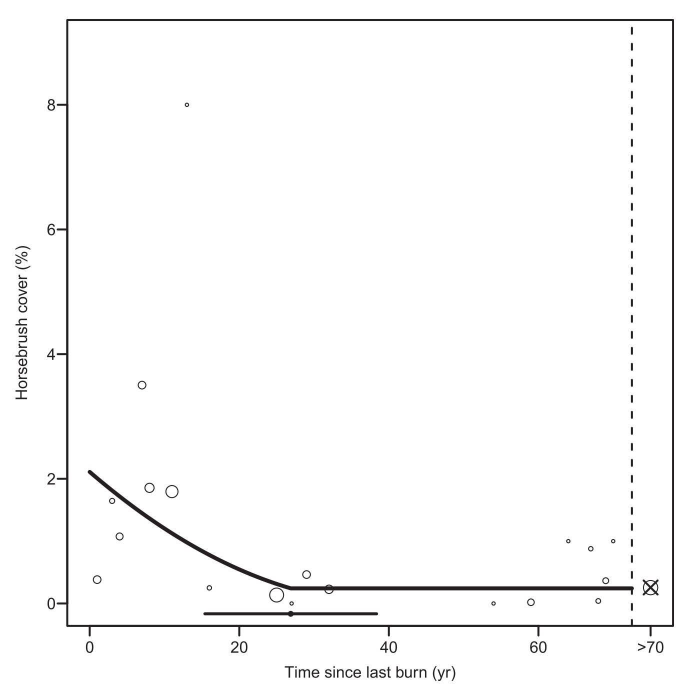

Fig. 3. Response of horsebrush cover to time since last burn (TSLB). Plot shows mean cover for each year (○; greater size of the symbol indicates more samples from that year; see Table 1 for the actual number of plots sampled in a given year) and mean of the >70-yr TSLB (⊗, $n = 31$); segmented relationship between year since last burn and percent sagebrush cover (solid curve); estimated threshold of TSLB when rates of change in cover change (•; displayed along the lower margin of the plot); and 95% confidence interval of the threshold (heavy solid line; displayed along the lower margin of the plot).

and it remained at 31% ($CI_{0.95}$ = 27%–34%) for the remainder of the range of TSLB observed. Furthermore, mean sagebrush cover for the 31 image samples from locations with >70 yr TSLB was slightly less than the plateau at 23% ($CI_{0.95}$ = 20%–27%).

Horsebrush cover was estimated at 2% in the burn year (Fig. 3). During Phase 1, horsebrush cover is initially high at 2% ($CI_{0.95}$ = 0.7%–3.9%), but cover decreases each year for 30 ± 6.6 (SE) yr TSLB. The arcsine-square root of cover changed linearly at a rate of −0.003 ± 0.0010 (SE) units per year during Phase 1. Cover had reached a plateau of 0.2% ($CI_{0.95}$ = 0.3%–0.5%) where it transitioned from Phase 1 to Phase 2. Mean horsebrush cover for the 31 image samples from locations with >70 yr TSLB was virtually the same as the plateau in Phase 2, at 0.3% ($CI_{0.95}$ = 0.1%–0.5%).

Bitterbrush cover was 0% in the fire year (Fig. 4). During Phase 1, bitterbrush cover increased each year until it reached a plateau at 6 ± 2.4 (SE) yr after burn. The arcsine-square root of cover increased linearly at 0.030 ± 0.0191 (SE) units per year until cover reached the plateau at 2.8% ($CI_{0.95}$ = 2.1%–3.6%). Mean bitterbrush cover for the 31 image samples from locations with >70 yr TSLB was 7% ($CI_{0.95}$ = 3.6%–10.8%), which is greater than the plateau value.

Because sagebrush was the dominant shrub, response of total shrub cover to TSLB was similar to the response of sagebrush cover. Total shrub cover was 5% in the fire year (Fig. 5). During Phase 1, shrub cover increased each year until it reached a plateau at 18 ± 4.1 yr after burn. The arcsine-square root of cover increased linearly at 0.025 ± 0.0042 (SE) units each year and cover reached a plateau at the transition between Phase 1 and Phase 2 of 40% ($CI_{0.95}$ = 36.5%–43.0%). Mean shrub cover for the 31 image samples from locations with >70 yr TSLB was virtually the same as the plateau value at 38% ($CI_{0.95}$ = 32.0%–44.1%).

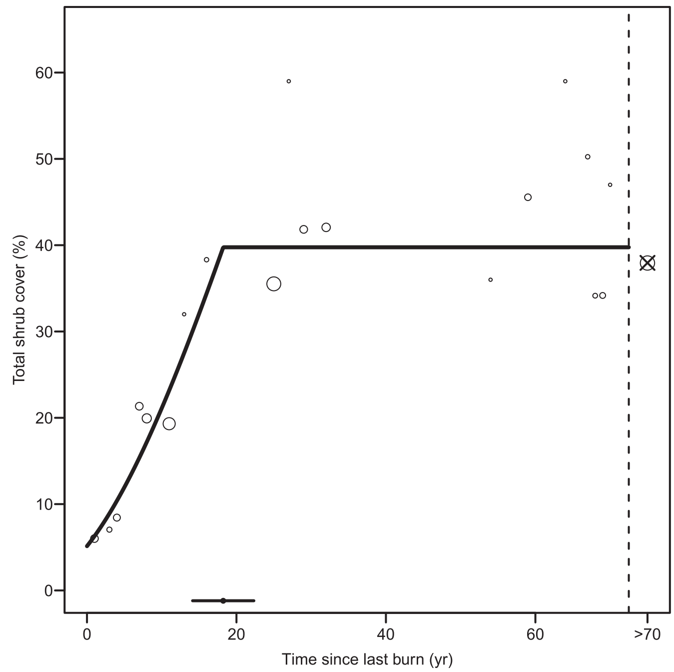

Fig. 5. Response of total shrub cover to time since last burn (TSLB). Plot shows mean cover for each year (○; greater size of the symbol indicates more samples from that year; see Table 1 for the actual number of plots sampled in a given year) and mean of the >70-yr TSLB (⊗, n = 31); segmented relationship between year since last burn and percent sagebrush cover (solid curve); estimated threshold of TSLB when rates of change in cover change (•; displayed along the lower margin of the plot); and 95% confidence interval of the threshold (heavy solid line; displayed along the lower margin of the plot).

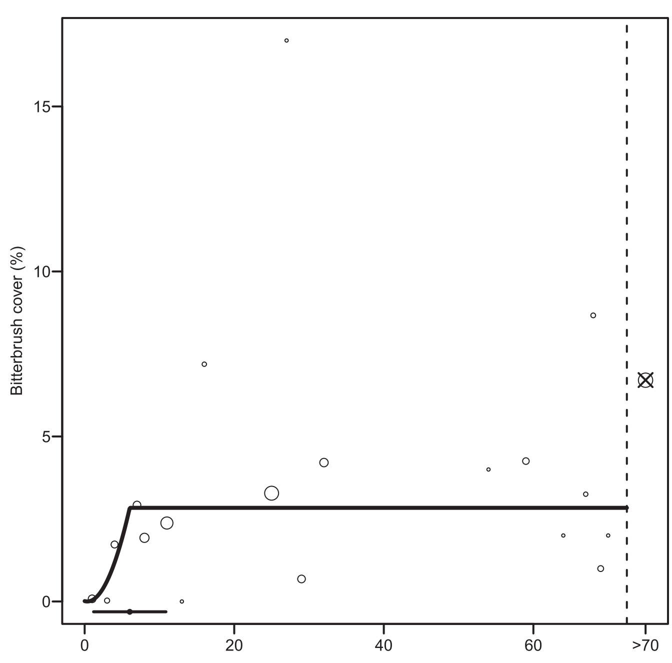

Fig. 4. Response of bitterbrush cover to time since last burn (TSLB). Plot shows mean cover for each year (○; greater size of the symbol indicates more samples from that year; see Table 1 for the actual number of plots sampled in a given year) and mean of the >70-yr TSLB (⊗, n = 31); segmented relationship between year since last burn and percent sagebrush cover (solid curve); estimated threshold of TSLB when rates of change in cover change (•; displayed along the lower margin of the plot); and 95% confidence interval of the threshold (heavy solid line; displayed along the lower margin of the plot).

4. Discussion

Shrub cover change in response to fire in a mountain big sagebrush community over a 70-yr period was defined. Using landscape-scale sampling methods and an extensive fire chronosequence, we developed models that described how sagebrush, bitterbrush, and horsebrush respond to TSLB. These data agree, for the most part, with previous reports of shrub cover change after fire in mountain big sagebrush communities (Bunting et al., 1987; Lesica et al., 2007; Sankey et al., 2008). We report estimates of shrub cover change rates and steady-state cover that are applicable for development of burning best management practices on mountain big sagebrush communities to meet shrubland management objectives.

4.1. Data and model characteristics

Shrub response to TSLB was best characterized with Model 4, a linear plateau model, according to the F-tests. Unique to this study, the fire chronosequence record was 4- to 12-times greater than the period of postfire shrub cover increase, and steady-state cover values were based on records from a period of greater than 50 yr of known fire history. As a result, we were able to establish steady-state shrub cover from the TSLB range where cover was not a function of TSLB (i.e., Phase 2). We avoided making assumptions about a “recovered state” or extrapolating from within the TSLB range where cover was a function of TSLB (i.e., Phase 1). Furthermore, the >70-yr TSLB mean shrub and horsebrush cover values fall within the confidence interval (Figs. 3 and 5) of the steady-state shrub and horsebrush cover estimates. The >70-yr TSLB mean sagebrush and bitterbrush cover estimates were slightly less and greater, respectively, then the steady-state cover estimates. Because only the lower bounds of TSLB were known for the >70-yr-TSLB data, inclusion in regression was problematic. Thus, these data were reported independently for comparison with steady-state cover values. Overall, we were able to identify distinct phases when shrub cover was either dynamic with respect to TSLB or unresponsive to TSLB (i.e., steady state).

4.2. Model comparison

Based on the current model, sagebrush cover is calculated to be 4, 15, and 30% in 6, 12, and 18 yr after fire. These data agree with Bunting et al. (1987) who reported that cover returned to pre-fire levels in 15–20 yr. By contrast, Lesica et al. (2007) reported a period of 32 yr to achieve assumed pre-fire cover levels. Assuming that the 30% sagebrush cover that we estimated at the end of Phase 1 was the "preburned" and "recovered" value, the model of Lesica et al. (2007) predicted that sagebrush cover would be 0.3, 3, and 30% at 0, 16, and 32 yr after fire, respectively. Furthermore, sagebrush cover would not exceed 15% until between 27 and 28 yr after fire. Because Lesica et al. (2007) did not describe why they chose to constrain the regression line to pass through the origin; it is not possible to determine why the period of sagebrush increase to assumed pre-burn levels (i.e., Phase 1) did not completely agree between studies. Regardless of this discrepancy, both models predicted that sagebrush cover increased at an increasing rate.

Total shrub cover reaches Phase 2 values in 18 yr. This is shorter than what Sankey et al. (2008) reported, using satellite imagery, from the same mountain big sagebrush communities. In addition, the predicted recovery rate was linear rather than curvilinear as was reported in the current study and elsewhere (Lesica et al., 2007). Their model was fitted to data that were the means ($n = 100$, pixels were 10×10 m) from 15 polygons of known TSLB and 1 polygon with >70 yr TSLB. Based on this model, total shrub cover increased at 1.4% each year, whereas the current model predicted an increasing recovery rate (e.g., from 0 to 1 yr TSLB total shrub cover increases 0.9%, but between 17 and 18 yr TSLB shrub cover increases 2.9%). Regardless of the differences in recovery rates, the plateau of total shrub cover from Sankey et al. (2008) and the current study were the same at 40%.

4.3. Model application: an example

Shrub dynamics in response to TSLB that we report are applicable for development of best management practices that meet livestock production and wildlife habit objectives. For example, sheep carrying capacity of rangeland and sage grouse-nesting habitat can be considered simultaneously when determining whether fire should be used as a management tool. Sheep carrying capacity was significantly enhanced in mountain big sagebrush communities up to 30 yr after fire (Harniss and Murray, 1973), but fire temporarily removed food and cover species that may be important to wildlife (Ferguson, 1968; Crawford et al., 2004). The recommended sagebrush cover for sage grouse-nesting habitat in mountain big sagebrush communities is 15–25% (Connelly et al., 2000). Based on the current data, mean sagebrush cover reaches 15% in 12 yr TSLB and reaches 25% 4 yr later. Thus, when considering the current data and that sheep carrying capacity (Harniss and Murray, 1973) and sage grouse-nesting habitat (Connelly et al., 2000) may diminish as sagebrush cover approaches the end of Phase 1 (31% at 19 yr TSLB), a shrub management plan could be developed that utilizes an alternating, mosaic-type (Lesica et al., 2007) repeated-burn strategy when sagebrush cover exceeds 25%. For the current study area, this would indicate that a burn could be repeated at 17 yr TSLB.

5. Implications

Based on available peer-reviewed literature, we believe this work provides land managers with a more complete description of postfire change in sagebrush, antelope bitterbrush, and spineless horsebrush cover in mountain big sagebrush-dominated rangelands. The chronosequence spans a period of time that is several times greater than the responsive phase for any of the species and shows a long period when the expected change in cover bares no relation to TSLB. These data were the result of a sample-rich investigation in which postfire cover responses of sagebrush, bitterbrush, and horsebrush were modeled from an extensive 70-yr fire chronosequence. Because of recent technological advances in remote sensing and geographical information systems, we were able to collect many large samples (>80 m^2/sample location) of shrub vegetation across an extensive landscape. We acknowledge that postfire variations in climate, soils, and management likely influenced average time to phase thresholds. However, managers can use the relationships between measured shrub presence and TSLB to formulate shrubland management plans that meet wildlife habitat and livestock production objectives.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jaridenv.2014.12.005.

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