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Sagebrush Control: At What Canopy Cover Is It Economically Justified?

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Abstract

We determine the economic threshold level for big sagebrush control based on 18 yr of forage-response data from an experiment conducted in Carbon County, Wyoming. We analyze the impacts of climatic variables and treatment site characteristics, such as sagebrush abundance levels, precipitation, and understory composition, on forage response and threshold level. We find that sagebrush canopy cover levels, April precipitation, May soil moisture, and understory composition are statistically significant factors in explaining forage response to sagebrush treatment. Forage yield across treated and untreated plots for 10 canopy cover levels, ranging from 4% to 40%, are analyzed via panel data regression techniques. We further investigate the impact of variability in precipitation and understory characteristics on economic outcomes of sagebrush control by analyzing three scenarios. Scenario 1 uses actual forage response data that include all variability from precipitation and understory composition. Scenario 2 uses regression-predicted yields across plots assuming average precipitation and soil moisture conditions. Scenario 3 uses regression-predicted yields assuming average precipitation, soil moisture, and understory characteristics across plots. Net present values based on value of grazing (for estimated yield differences between treated and untreated plots assuming 50% forage utilization) compared to treatment cost across sagebrush cover levels are estimated across these three scenarios. Results indicate that the economic threshold level of sagebrush infestation for the study period was between 8% and 24% for the analyzed scenarios. This indicates variability in precipitation and understory composition impact forage response and the resulting economics of sagebrush control. We conclude that range managers should consider potential control site characteristics and long-range weather forecasts when contemplating sagebrush control.

Resumen

Determinamos el nivel del umbral económico para el control de la artemisa basados en 18 años de datos sobre la respuesta del forraje en un experimento realizado en Carbon County, Wyoming. Analizamos el impacto de variables climáticas y características del sitio tales como niveles de abundancia de artemisa, precipitación y la composición abajo del dosel en la respuesta del forraje y el nivel de umbral. Encontramos que los niveles de cobertura aérea de la artemisa, la precipitación de abril, la humedad del suelo de mayo y la composición son factores estadísticamente significantes para explicar la respuesta del forraje en el tratamiento de la artemisa. El rendimiento de forraje a lo largo de las parcelas tratadas y no tratadas para diez niveles de cubierta aérea fluctuaron del 4% al 40% son analizados por medio de técnicas de regresión de datos panel. Además investigamos el impacto de la variabilidad en precipitación y características debajo del dosel en los resultados económicos del control de la artemisa analizando tres escenarios. En el escenario uno, se usaron los datos de la respuesta actual del forraje la cual incluye toda la variabilidad de la precipitación y composición de abajo del dosel. El escenario dos, usa rendimientos predichos de regresión a lo largo de las parcelas asumiendo precipitación promedio y condiciones de humedad del suelo. El escenario tres usa rendimientos predichos de regresión asumiendo precipitación promedio, humedad del suelo y características de abajo del dosel a través de las parcelas. Valores presentes netos basados en el valor del pastoreo (estimados de las diferencias entre los rendimientos de las parcelas tratadas y no tratadas asumiendo un 50% de utilización del forraje) comparado con el costo del tratamiento a través de los niveles de cobertura de la artemisa son estimados a través de estos tres escenarios. Los resultados indican que el nivel del umbral económico de infestación de artemisa para el periodo de estudio fue entre 8% y 24% de los escenarios analizados. Esto indica que la variabilidad en precipitación y composición abajo del dosel impacta la respuesta del forraje resultando en el control económico de la artemisa. Concluimos que manejadores de pastizales deben considerar las características potenciales de control en el sitio y rangos amplios de pronósticos de tiempo cuando consideren el control de la artemisa.

Key Words: economic threshold, environmental factors, understory composition

INTRODUCTION

Sagebrush–grass ecosystems occupy as much as 109 million hectares of the western United States, including 60 million hectares of big sagebrush (*Artemisia tridentata* Nutt.) (Beetle 1960; Blaisdell et al. 1982). Given the importance of sagebrush–grass ecosystems as a source of forage for livestock and wildlife, agricultural producers and government agencies have invested heavily in sagebrush control. More than 1 million

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hectares of sagebrush were treated chemically from the 1950s to the mid-1970s in Wyoming alone (Freeburn 1979). Spraying with 2,4-D is one of the most successful and cost-effective methods for controlling sagebrush given sufficient spring moisture and active growth (Mueggler and Blaisdell 1958; Krenz 1962; Kearl 1965; McDaniel and Balliette 1986; Wambolt and Payne 1986; Watts and Wambolt 1989; McDaniel et al. 1991). However, forage response to sagebrush control using 2,4-D varies widely across space and time, ranging in past studies from 0% to 400% (Kearl 1965). Identifying the economic threshold level at which sagebrush control is feasible will improve the allocation of resources to sagebrush control and the resulting economic outcomes.

Researchers have hypothesized a number of potential causes of variability in forage response across space and time, including heterogeneity in the following factors: initial sagebrush density (Bastian et al. 1995); composition and vigor of understory vegetation (Alley and Bohmont 1958; Hedrick et al. 1966; Schmisseur 1981; McDaniel and Balliette 1986; McDaniel et al. 1992); sagebrush mortality rates following treatment (Bartolome and Heady 1978; Sturges 1986; Tanaka and Workman 1988); snow accumulation and retention (Sonder and Alley 1961; Sturges 1977); precipitation (Maier et al. 2001); soil moisture, nitrogen, and temperature (Hedrick et al. 1966; Lauenroth and Whitman 1977); elevation, slope, aspect, and exposure (Johnson and Payne 1968; Mendelsohn 2010); and grazing management (Johnson 1969). Although anecdotal evidence suggests that these site-level characteristics and environmental factors influence forage response, few studies have identified statistically significant relationships. We use canopy cover as the primary indicator for threshold abundance at which control becomes economically feasible. Given the literature, we also hypothesize that precipitation, soil moisture, and understory composition impact forage. Thus, our research focuses on the impact of initial canopy cover, precipitation, soil moisture, and understory composition on forage response and the resulting economic outcomes from sagebrush control.

Bastian et al. (1995) analyze the first 4 yr of forage response from the same study area and plots used in this analysis. The authors use regression to normalize response across plots for precipitation and soil moisture differences. They find that higher initial levels of sagebrush canopy cover resulted in higher forage productivity after control. Because the authors lacked long-term observations of forage response, they perform a sensitivity analysis around control longevity horizons (15, 20, or 25 yr) and predict the nature of forage response based on past literature. The authors conclude that the breakeven for controlling sagebrush (i.e., an estimated net present value [NPV]of zero) could occur at a canopy level as low as 12%, assuming that the longevity of control is at least 25 yr and 24% for longevity lasting only 15 yr. The authors lacked the data to analyze the true nature of forage response over time across the different plots given variability in precipitation and understory composition. Their analysis suggests that the accuracy of threshold estimates could be improved with observations over a longer time period.

McDaniel et al. (2005) evaluate forage response across various sites in New Mexico that differ in initial sagebrush abundance, rate of tebuthiuron application, and sagebrush canopy over time measured every fifth year after control. McDaniel et al. (2005) use a two-step regression procedure relating the change in sagebrush canopy cover over time to the number of years following treatment. The authors find that grass yields were higher on treated sites as compared to untreated sites. A nonlinear S-shaped curve best described overstory–understory relationships and the time path of sagebrush recovery. The authors also indicate that grass yields were highly variable over time because of weather conditions. Torell et al. (2005) utilize the data and regression procedures reported in McDaniel et al. (2005) to predict forage response relative to the changing sagebrush over time. They calculate NPV of sagebrush control across the different study sites using the forage-response predictions. Their findings indicate that overstory–understory relationships impact economic outcomes for sagebrush control.

Precipitation drives soil moisture and is, in turn, expected to positively impact forage response. Laurenroth and Whitman (1977) find that soil moisture and soil temperature are statistically significant predictors of needle-and-thread grass (*Stipa comata* Trin. & Rupr.) biomass in their regression analysis. Torell et al. (2011) find soil moisture to be a better predictor of grass yields than the traditionally used measure of seasonal rainfall totals. Dean (1983) finds that annual precipitation does not explain variability in cool-season grass production following sagebrush control in western Wyoming, but Smith et al. (2005) find that April precipitation is a statistically significant predictor of cool-season grass production across a number of Wyoming sites. Overall, this literature suggests that early to late spring precipitation and/or soil moisture should positively impact forage response in areas dominated by cool-season grasses.

Initial site conditions affect forage response from sagebrush control. McDaniel et al. (1992) indicate that sites with lower initial forage production experience less response to sagebrush control. McDaniel and Balliette (1986) conclude that a higher abundance of galleta grass (*Hilaraia jamesii* [Torr.] Benth.) relative to blue grama (*Bouteloua gracilis* [Willd. ex Kunth] Lag. ex Griffiths) increased grass production following sagebrush control. Dean (1983) concludes that plots with lower grass production have fewer seeds available to help increase grass cover after sagebrush control. Overall, this suggests that the initial forage productivity and species composition impact forage yields after sagebrush control.

This study utilizes a long-term data set from a sagebrush control experiment in Carbon County, Wyoming, of the Northern Rocky Mountain region to investigate the influence of site characteristics and environmental factors on forage response and the resulting economic outcomes from sagebrush control. Forage yield across treated and untreated plots for 10 canopy cover levels, ranging from 4% to 40%, are analyzed via panel data regression techniques. We further investigate the impact of variability in precipitation and understory characteristics on economic outcomes of sagebrush control by analyzing three scenarios. Scenario 1 uses actual forage response data that include all variability from precipitation and understory composition. Scenario 2 uses regression-predicted yields across plots assuming average precipitation and soil moisture conditions. Scenario 3 uses regression-predicted yields assuming average precipitation across the study period, average soil moisture across the study period by plot, and understory characteristics across plots. NPVs based on value of grazing (for estimated yield differences between treated and untreated plots assuming 50% forage utilization) compared to treatment cost across sagebrush cover levels are estimated across these three scenarios. Comparison of these NPVs reveals that site characteristics, such as sagebrush abundance levels and understory composition, along with environmental conditions over time, sufficiently impact forage response to influence the economic threshold level of sagebrush control.

MATERIALS AND METHODS

Study Area and Forage-Response Data

The forage-response data are from a location in south-central Wyoming, approximately 19 km northeast of Saratoga in Carbon County. The approximate geographic center of the study area is lat 41°32′22.62″N, long 106°40′48.66″W. The study area is on the plain below the west slope of the Medicine Bow Mountains at an elevation of 2 245 m and receives approximately 33 cm of precipitation annually. Vegetation in the area is dominated by an overstory of Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis* Beetle & Young). The herbaceous layer consists primarily of thickspike wheatgrass (*Elymus lanceolatus* [Scribn. & J. G. Smith] Gould) and needle-and-thread grass with several minor graminoids, including Kentucky bluegrass (*Poa pratensis* L.), Sandberg bluegrass (*Poa secunda* J. Presl), and needleleaf sedge (*Carex eleocharis* L. H. Bailey). Forbs are generally not abundant within the study site.

Within an area encompassing 11.2 km^2, 20 study sites were selected across a range of big sagebrush abundances, as measured by canopy cover, but on similar sandy soils. The experimental plots' physical proximity to each other ensures similar climate, topography, plant communities, and historical use. The range of sagebrush abundance may be explained largely by topographic positioning, resulting in differential snow accumulation over winter. Low sagebrush abundance occurred on sites exposed to more wind, while the higher sagebrush abundance levels were in defilade positions where snow accumulates. Intermediate sagebrush cover occurred on generally level terrain. Each pair of treated and untreated plots differs from the others in their starting sagebrush cover. Sites had big sagebrush canopy cover over a gradient ranging from approximately 4% to 40%. This range of sagebrush of cover is much larger than typically reported in the literature, and it allows us to more accurately evaluate economic threshold levels.

On each study site, two experimental units (approximately 30×30 m) with similar big sagebrush abundances were delineated. The sagebrush cover on each experimental unit was verified by sampling 100 points each with two 33-m line point transects (National Applied Resources Sciences Center 1996) that were permanently marked at the ends with a steel stake. The sagebrush cover measured on each experimental unit was within 2% of the designated treatment abundances of 4–40% in increments of 4%. One of each pair of experimental units was randomly determined for treatment and nontreatment. Two replicate pairs for each sagebrush abundance level were included in the design. This design fits a two-factor (sagebrush abundance and sagebrush removal) analysis of variance statistical model. Big sagebrush was treated 1 June 1987 by spraying using a tractor-mounted boom at 2.2 kg · ha^{-1} rate with 2,4-D LV Ester. Because of fortuitous growth stage and effective application, live sagebrush cover was effectively zero after treatment, as the sagebrush mortality rate was at least 96% or higher across all sites.

Peak standing biomass of all herbaceous vegetation was measured in late July each year of the study (1987 through 2004) by harvesting herbaceous vegetation on 0.5-m^2 quadrats protected by movable cages (six per experimental unit). Sample material was dried at 60°C, weighed, and reported in kg · ha^{-1}. Percent composition of understory by weight was determined in the first year of the study but was not available for the rest of the study period for this analysis. The sagebrush cover was again sampled after the end of the study in 2010 using the same method as before and using the same transects marked with steel stakes. Precipitation information was obtained from National Oceanic and Atmospheric Administration records of Saratoga. These data consist of daily precipitation and were summarized as monthly totals for this analysis. Gravimetric soil moisture content was sampled at three locations in each experimental unit annually during May in the top 45 cm of soil. Data were reported as percent weight of water in grams per 100 g of dry soil.

Analysis of Forage Response

Data were first analyzed graphically by sagebrush cover density to visually assess data characteristics and potential functional forms for the regression models. Descriptive statistics and correlation analyses were estimated across treated and untreated sites to further analyze potential characteristics that might impact forage response. Regression analyses of the data were then conducted. Given the nature of the data, regression analyses must account for statistical issues sometimes associated with time-series and cross-sectional data. The forage-response models were estimated in SAS using the TSCSREG procedure, based on the Parks method (Parks 1967; SAS 2009). The Parks method is an autoregressive model in which the random errors, u_{it}, exhibit heteroskedasticity ($E[u^2{}_{it}] = \sigma_{ii} \neq 0$), contemporaneous correlation ($E[u_{it}\ u_{jt}] = \sigma_{ij} \neq 0$), and autocorrelation ($u_{it} = \rho_i u_{i,t-1} + \varepsilon_{it}$). The Parks method assumes a first-order autoregressive error structure with contemporaneous correlation between cross sections. This method accounts for the unique statistical problems associated with the panel data set used in this analysis (i.e., time-series observations for each of several plots in our experiment).

Economic Analysis

Net revenue (i.e., revenue − cost) from sagebrush control must be discounted using an NPV framework to account for differences in the timing and magnitude of forage response across plots (Barry et al. 2000). Given the data were observed annually (i.e., forage data were collected and analyzed in discrete time periods), the NPV of net revenues from sagebrush control, expressed as dollars per hectare, are calculated using the following formula:

$$\mathrm{NPV} = -\mathrm{INV} + P_1/(1+i)^1 + P_2/(1+i)^2 + \ldots + P_N/(1+i)^N \quad [1]$$

where NPV=net present value of net revenue over a multiyear period, INV=cost of sagebrush control and grazing deferment, P_n=revenue from increased forage production in year n, n=1, …, N, and i=discount rate.

The cost of sagebrush control for each level of initial sagebrush cover includes the cost of purchasing and applying 2,4-D ($26.25 · ha^{-1}, assuming recommended application rates per hectare and current prices deflated to 2004 dollars)[1] plus the cost of deferring grazing for 1 yr after treatment. The cost of deferred grazing depends on the initial quantity of forage available, and it is calculated as follows: forage biomass data from untreated plots is multiplied by a 50% utilization rate and a conversion factor of 360 kg DM · AUM^{-1} (Society for Range Management 1974; Scarnecchia and Kothmann 1982; Bastian et al. 1995) to estimate the animal unit months (AUM) of grazing forgone. Forgone AUMs are then multiplied by a representative net forage value to calculate the opportunity cost of deferred grazing.

The forage value is based on the "11 western states lease rate" for each year of the study, 1987–2004 (National Agricultural Statistics Service for Wyoming Agricultural Statistics 2008), deflated to 2004 dollars using the producer price index (Bureau of Labor Statistics 2008) and then averaged. This average deflated lease rate was used in our analysis per the American Agricultural Economics Association (AAEA) task force's guidelines for estimating commodity costs and returns (AAEA Task Force on Commodity Costs and Returns 2000). This lease rate ($12.58 · AUM^{-1}) was then reduced by 30% to adjust for average landlord services provided in private lease rates (Bastian et al. 1995; Bartlett et al. 2002; Torell et al. 2005). Thus, the net forage value used in our analysis is $8.81 · AUM^{-1}. This represents the net lease value of forage to be used for livestock grazing.

The discount rate (i) was based on returns to 30-yr US Treasury bonds from 1987 through 2001 (2002–2004 returns were not reported in the available source). These returns were adjusted by the percent change in the gross domestic product chain-type price index, as reported in the Economic Report of the President, from the preceding year to obtain an estimate of the real interest rate (US Government Printing Office 2007). The estimated 15-yr average real rate of interest, 4.67%, is the base discount rate assumed in this analysis. Sagebrush control may be impacted by a number of factors and is therefore not a riskless investment. Thus, a discount rate of 6.67%, which includes a 2% risk premium over the base rate, is also used for comparison.

Variability in treatment site characteristics and environmental factors could affect forage response and the overall economic feasibility of controlling sagebrush. Three forage-response scenarios are therefore constructed to better understand the potential impact of environmental conditions and site characteristics on economic outcomes associated with sagebrush control.

[1]Jim Cotterman, assistant supervisor, Platte County Weed and Pest Control District, personal communication, August 2009. Bunker Shepard, aerial applicator, Wheatland, Wyoming, personal communication, August 2009.

The first scenario used for economic analysis contains actual forage response (defined as the difference between actual forage yields on treated vs. untreated plots that had the same pretreatment sagebrush abundance) observed in the experimental plots over the study period. This response scenario captures the effect of variability in site characteristics and precipitation on forage response.

The second forage-response scenario is constructed by inserting the average April precipitation of the study period (1987–2004) and average May soil moisture for each site across the study period into the estimated forage-response functions (one function for treated plots and another for untreated plots). Forage yields for both untreated and treated sites are then predicted for each sagebrush abundance level from the estimated regression models to predict the average forage response for average moisture conditions over the study period (i.e., predicted forage biomass for a treated plot minus predicted forage biomass for its respective untreated plot given average precipitation and soil moisture for the site across the study period). This scenario is designed to represent an average expectation for precipitation and allow us to examine the impact of variable precipitation on the economic outcomes of sagebrush control as compared to the first scenario.

The third scenario again uses the estimated forage-response functions as a way to control for variability across plots as it relates to beginning understory characteristics for each sagebrush abundance level. This scenario uses average precipitation and soil moisture as in the second scenario, and it normalizes beginning understory characteristics across plots to predict forage responses. This forage-response scenario is estimated to evaluate the potential impacts of understory characteristics on economic outcomes of sagebrush control as compared to the second scenario. Comparison of the estimated NPVs for the three forage-response scenarios allows us to evaluate the sensitivity of economic threshold levels of initial sagebrush abundance to variability in precipitation, soil moisture, and site characteristics given the study area and time period.

RESULTS

Graphical analyses indicated that forage response over the study period was, as expected, nonlinear over time as forage response seemed to peak on treated plots between years 7 and 10, but there was much variability in overall yields across plots and time. Figure 1 illustrates the net difference in forage response between treated and untreated sites for the actual observed data at 24% and 40% sagebrush abundance levels, respectively. Forage response reaches its highest level in year 7 and then generally declines after year 9 of the study. Moreover, the variability in response for the two plots suggests that something other than canopy cover may be impacting forage productivity. While we do not show graphs across all abundance levels in the interest of brevity, it should be noted that they all showed variability over time, although the response pattern varied. One factor that may be driving variability in forage response is precipitation over the study period. Figure 2 indicates that April and May precipitation

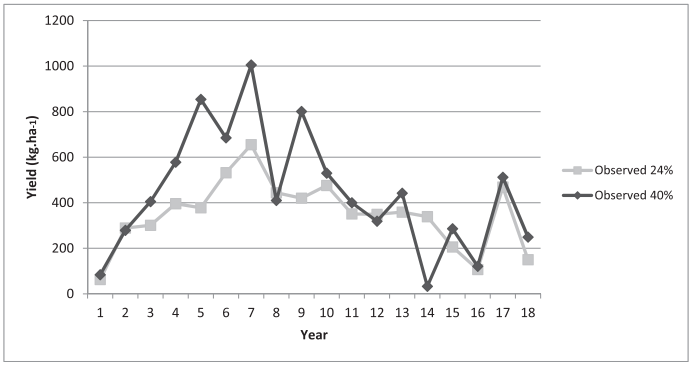

Figure 1. Observed yield difference in forage productivity for plots with pretreatment sagebrush canopy cover of 24% and 40%.

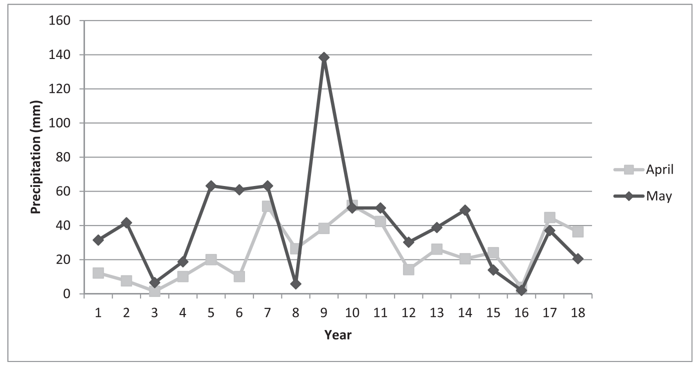

Figure 2. Precipitation over the study period during April and May.

were highly variable over the study period, but generally May precipitation was higher during the first half of the study.

Descriptive statistics regarding initial site characteristics and overall forage response across sites are reported in Tables 1 and 2. Clipped forage species were separated and measured as a percentage of total weight in 1987. These percentages are presented in Table 1 in addition to sagebrush canopy and forage biomass. Table 1 indicates that forage biomass generally decreases across the untreated sites in 1987 as sagebrush abundance levels increase, but there is certainly not a perfect correlation. For example, the average forage biomass in 1987 across the untreated plots and sagebrush levels is 282.9 $kg \cdot ha^{-1}$, but we observe forage biomass levels above the average for the 4%, 8%, 12%, 20%, 24%, and 32% canopy cover levels (Table 1). Those sites also tend to have above-average beginning percentages of needle-and-thread grass, and they generally have below-average beginning percentages of thickspike wheatgrass with the exception of the 32% canopy cover. We see forage yield below the average for the 16%, 28%, 36%, and 40% sagebrush abundance levels, with the 28% and 40% sagebrush cover levels having the least forage biomass production (186 and 158 $kg \cdot ha^{-1}$, respectively). The below-average sites generally have higher ratios of thickspike wheatgrass relative to needle-and-thread grass for beginning understory composition. The percentage of needle-and-thread grass tends to decrease with sagebrush abundance, while thickspike wheatgrass generally increases. On average, needle-and-thread grass was 19.6% of total forage biomass production across the sites, but there was relatively large variability across sites as indicated by the standard deviation. Interestingly, in those instances where needle-and-thread grass is a relatively smaller proportion of forage production, overall forage production seems to decline across the sites as well. Thickspike wheatgrass ranged from 4.69% to 70.75% and averaged 40.10% of forage biomass (Table 1). It was expected at the time of treatment that the proportion of needle-and-thread grass should increase after sagebrush control and that thickspike wheatgrass would decline. The proportion of forbs and other grasses tended to decline as sagebrush abundance increased, but there is not a perfect correlation. These results suggest that more than just sagebrush abundance explains forage production on the untreated sites, which were in the same area and should have experienced the same precipitation and temperature conditions.

Table 2 reports the ending forage biomass for the study period (observed in 2004), the total forage over the study period, and the ending sagebrush canopy cover (as measured in 2010) for the treated and untreated sites. Generally, ending forage and total forage production over the study period are less for the untreated sites than treated sites, as expected. Final forage biomass was, on average, 258.8 $kg \cdot ha^{-1}$ less for untreated sites compared to treated sites. Average forage production over the study period was 5 607.5 $kg \cdot ha^{-1}$ higher for the treated sites as compared to the untreated sites (Table

Table 1. Untreated site understory characteristics in 1987 (year of treatment).

Sagebrush cover (%)	Forage biomass ($kg \cdot ha^{-1}$)	Needle-and-thread grass (%)[1]	Thickspike wheatgrass (%)	Other grasses (%)	Forbs (%)
4	326	27.85	4.69	50.40	17.09
8	349	28.85	22.06	31.66	17.54
12	346	28.35	31.18	26.33	14.08
16	241	17.55	30.12	39.00	13.15
20	297	23.10	27.44	36.36	12.96
24	299	25.85	48.26	19.83	6.12
28	186	3.33	70.75	17.10	8.98
32	359	26.04	32.98	21.64	19.36
36	268	5.71	63.43	18.54	12.46
40	158	9.68	69.87	18.54	1.77
Average	282.9	19.63	40.10	27.94	12.35
Standard deviation	69.46	9.91	22.13	11.12	5.42

[1]Percentage of forage biomass as measured by weight.

Table 2. Observed forage biomass over study period (1987–2004), ending forage biomass (2004), and ending sagebrush cover (2010) across untreated and treated sites and means comparison.

Beginning sagebrush cover (%) (1987)	Untreated sites: Ending forage (2004) (kg · ha^{-1})	Untreated sites: Total forage (1987–2004) (kg · ha^{-1})	Untreated sites: Ending sagebrush cover (%) (2010)	Treated sites: Ending forage (2004) (kg · ha^{-1})	Treated sites: Total forage (1987–2004) (kg · ha^{-1})	Treated sites: Ending sagebrush cover (%) (2010)	Means test for treated and untreated t statistic[1]
4	332	6 799	6.5	452	9 826	1.5	3.03*
8	277	7 298	13.0	690	12 486	5.8	4.52*
12	271	6 185	17.33	602	11 195	6.5	4.58*
16	210	6 020	14.5	479	10 841	5.5	4.40*
20	370	6 604	19.3	617	11 668	3.0	4.25*
24	344	6 619	28.5	494	12 903	7.3	5.29*
28	113	4 827	34.5	280	8 892	11.8	3.54*
32	358	7 652	29.8	516	14 348	34.8	4.25*
36	139	6 521	40.8	623	14 448	14.5	4.31*
40	122	4 102	40.5	371	12 095	25.8	5.21*
Average	253.6	6 262.7	24.5	512.4	11 870.2	11.6	
Std. Dev.	100.96	1 074.7	12.0	125.5	1 791.5	10.7	

[1]Difference in yield between treated and untreated sites for each sage cover level (1987–2004). * indicates significance at $\alpha = 0.01$.

2). A comparison of the means over the study period across sagebrush cover levels confirms that sagebrush control resulted in a statistically significant increase in forage production in all cases. Reported t statistics range from 3.03 to 5.29 across abundance levels, and all are significant at the $\alpha = 0.01$ level (Table 2). The variability in forage response across the sagebrush abundance levels is obvious given the reported standard deviations for the ending and total forage statistics (Table 2). This variability across sites is further illustrated by measurements of sagebrush abundance in 2010 across treated and untreated sites (Table 2). In all but one case, sagebrush cover increased from pretreatment levels on the untreated sites, but that level of increase was highly variable across the sites. The level of sagebrush cover after treatment also increased for the treated sites. In all but one case (32% abundance), sagebrush canopy level in 2010 is less than pretreatment abundance levels for the treated sites with an average of 11.6% cover across all treated sites. Again, however, there is relatively wide variability in the ending percent of canopy cover with a standard deviation of 12.0 for untreated sites and 10.7 for treated sites, compared to their respective averages of 24.5 and 11.6. As expected, these statistics suggest that other factors in addition to sagebrush cover impact forage response before and after control.

Table 3 reports correlation coefficients between beginning sagebrush cover, ending sagebrush cover, beginning forage, ending forage, total forage response, and understory characteristics across untreated and treated sites. Correlation coefficients for the untreated sites indicate that beginning, ending, and total forage production are highly and negatively correlated to initial sagebrush cover. Coefficients range between –0.58 and –0.44 (Table 3). Moreover, ending sagebrush cover is highly and positively correlated to beginning sagebrush abundance for untreated sites (0.96). This suggests that areas heavily infested with sagebrush may tend to move toward a state of higher sagebrush abundance as time passes. These coefficients suggest forage production and ending sagebrush canopy are highly correlated to initial sagebrush abundance. The percent of needle-and-thread grass is positively and highly correlated to forage production for the untreated sites (ranging from 0.85 for beginning forage to 0.70 for total forage), and it is highly but negatively correlated to sagebrush cover for the untreated sites. The correlations are again high but have a negative sign for thickspike wheatgrass as percent of initial forage biomass when examining forage production on untreat-

Table 3. Estimated correlation coefficients between beginning sagebrush cover, ending sagebrush cover, beginning forage, ending forage, total forage response, and understory characteristics across untreated and treated sites.

	Untreated sites: Begin sage (%)	Untreated sites: Needle-and-thread (%)	Untreated sites: Thickspike wheatgrass (%)	Treated sites: Begin sage (%)	Treated sites: Needle-and-thread (%)	Treated sites: Thickspike wheatgrass (%)
Begin forage	−0.5751	0.8506	−0.7582	−0.1709	0.3652	−0.1522
End forage	−0.4976	0.8815	−0.76094	−0.3432	0.7622	−0.6451
Total forage	−0.4429	0.7034	−0.6923	0.4641	0.0780	0.0673
End sage (%)	0.9647	−0.7505	0.9331	0.7586	−0.4470	0.5705
Needle-and-thread (%)	—	1	−0.8485	—	—	—
Begin sage (%)	—	−0.69826	0.8525	—	—	—

Table 4. Estimated forage-response functions for untreated and treated sites (dependent variable is forage biomass).

	Untreated sites			Treated sites		
	Coefficient	*t* statistic	Elasticity[2]	Coefficient	*t* statistic	Elasticity[2]
Constant	141.4762	5.65**		−147.203	−2.57*	
sagecvr	−2.6942	−8.22**	−0.1704	8.6527	6.21**	0.2891
aprprcp	40.3261	2.77**	0.1120	117.4717	4.62**	0.1725
msoilmst	13.3282	8.36**	0.4043	20.5778	7.32**	0.0494
pctnatg[1]	—	—	—	3.9679	3.34**	0.0777
pctwhtg[1]	—	—	—	−2.2129	−3.47**	−0.0763
t	39.2865	6.29**	1.0727	88.0538	7.93**	1.2706
t^2	−2.3366	−7.44**	−0.7869	−4.9960	−8.97**	−0.8892
R^2	0.6844	—	—	0.7235	—	—

[1]The high correlation between beginning percentage of needle-and-thread grass (pctnatg), thickspike wheatgrass (pctwhtg), and initial sage cover (sagecvr) precluded inclusion in the forage-response function for untreated sites.

[2]Elasticity measures the percent change in yield given a 1% increase in the variable of interest. These elasticities are calculated as $\beta \cdot \bar{x}/\bar{y}$, where β is the coefficient of interest, $\bar{x}$ is the average of the independent variable of interest, and $\bar{y}$ is the average of the dependent variable. ** indicates significance at $\alpha = 0.01$, and * indicates significance at $\alpha = 0.05$.

ed sites. Thickspike wheatgrass has a 0.9331 correlation coefficient with ending sagebrush cover (Table 3). This suggests that the nature of the understory forage composition is likely an important factor explaining forage production on the untreated sites. This also points to its potential as an explanatory factor in explaining forage response overall when sagebrush is controlled.

The correlation coefficients for the treated sites tend to support the importance of understory characteristics in explaining forage response from sagebrush control (Table 3). Initial sagebrush cover is relatively highly and positively correlated to total forage response from control across the treated sites (0.4641). Moreover, the initial percent of needle-and-thread grass is highly correlated to ending forage production. Overall, it has a small but positive correlation with total forage production on treated sites. Thickspike wheatgrass has correlation coefficients with similar magnitudes but the opposite sign for untreated sites and forage production as compared to needle-and-thread grass (Table 3). The univariate analysis confirms that beginning understory characteristics as well as initial sagebrush abundance are potentially important in explaining forage response from sagebrush control. The overall magnitude of importance of these site characteristics is investigated in the multivariate regressions examining forage response across treated and untreated sites.

Regression Results

Given the above statistics, regression analyses testing different functional forms and variables of interest from the available data were conducted. The results indicate that the following models best explain biomass data from the untreated plots and treated plots:

$$\text{Untreated } Y_{it} = \beta_0 + \beta_1 \,\text{sagecvr}_i + \beta_2 \,\text{aprprcp}_t + \beta_3 \,\text{msoilmt}_{it} + \beta_4 \, t + \beta_5 \, t^2 + u_{it} \quad [2]$$

$$\text{Treated } Y_{it} = \beta_0 + \beta_1 \,\text{sagecvr}_i + \beta_2 \,\text{aprprcp}_t + \beta_3 \,\text{msoilmst}_{it} + \beta_4 \,\text{pctnatg}_i + \beta_5 \,\text{pctwhtg}_i + \beta_6 \, t + \beta_7 \, t^2 + u_{it} \quad [3]$$

where Y_{it}=yield (i.e., forage biomass) based on clip data from plot i in year t for either untreated or treated plot; β_x=estimated regression parameters, $x = \ldots, 7$; sagecvr$_i$=initial percent sagebrush cover (4–40) for each plot (i); aprprcp$_t$=April precipitation in each year (t) of the study period for the study area; msoilmst$_{it}$=soil moisture for May in each year (t) of the study period and corresponding plot (i); pctnatg$_i$=percent of initial forage biomass weight from needle-and-thread grass for each plot (i); pctwhtg$_i$=percent of initial forage biomass weight from thickspike wheatgrass for each plot (i); t=trend variable to account for forage response over time (1–18); t^2=square of trend variable to allow for nonlinearity in biomass across time; and u_{it}=error term.

The empirical estimates of the forage-response functions and associated elasticities are reported in Table 4. Elasticities are interpreted as the percentage change in yield given a 1% increase in the independent variable of interest, and they offer a way of comparing magnitudes of effects from the independent variables. The models' parameter estimates generally have the expected signs, and all are significant at the $\alpha = 0.01$ level with the exception of the constant for the treated-sites equation. The response function for untreated plots indicates a negative relationship between forage biomass and sagebrush cover, which reveals that forage production is increasingly suppressed at higher sagebrush densities. The response function for treated plots, in contrast, shows a positive relationship between initial sagebrush cover (i.e., before treatment) and forage biomass after treatment. This indicates that as initial sagebrush cover for a plot increases, the resulting benefit of treatment is increased forage biomass. The magnitude of the elasticity for initial sagebrush cover is greater for the treated-sites equation (0.2891) than for the untreated-sites equation (–0.1704), suggesting forage response from treatment is more sensitive to sagebrush abundance than forage yield on the untreated plots.

The April precipitation and May soil moisture variables are significant and positive in both the treated and the untreated models (Table 4). The associated elasticities indicate that forage yield is more sensitive to April precipitation in the treated-sites equation (0.1725) than the untreated-sites (0.1120) equation. May soil moisture has a greater impact on forage yield in the

Table 5. Net present value ($\$ \cdot ha^{-1}$) of forage response for observed forage response and predicted forage response using estimated forage-response functions controlling for variable precipitation over time, variable soil moisture over time, and variable understory characteristics across sites.

	Observed response		Predicted response for average precipitation and soil moisture		Predicted response given average precipitation, soil moisture, and understory across sites	
Discount (%):	4.67	6.67	4.67	6.67	4.67	6.67
Beginning sagebrush cover (%)a						
4	($6.48)	($9.63)	($2.52)	($6.18)	($17.98)	($19.54)
8	$12.41	$6.61	($3.70)	($7.21)	($14.36)	($16.42)
12	$11.13	$5.52	($1.03)	($4.92)	($8.60)	($11.46)
16	$9.40	$3.96	($2.32)	($5.97)	($4.24)	($7.63)
20	$12.11	$6.45	$9.62	$4.34	$3.80	($0.69)
24	$22.53	$15.80	$17.57	$11.16	$16.55	$10.37
28	$6.20	$2.03	$0.14	($3.88)	$18.62	$12.09
32	$28.99	$22.79	$32.89	$24.45	$27.15	$29.83
36	$35.76	$26.86	$19.03	$12.54	$33.94	$25.42
40	$40.05	$31.81	$20.09	$13.47	$34.79	$26.17
Average	$17.21	$11.21	$8.98	$3.78	$8.97	$4.81
Standard deviation	14.38	12.78	12.78	11.07	19.86	18.51

untreated-sites equation (0.4043) than April precipitation (0.1120), but May soil moisture has much less impact on forage yield in the treated-sites equation (0.0494). This indicates a decrease in competition for moisture after sagebrush is controlled and, hence, an increase in the marginal effect of precipitation on forage biomass. The initial percent of needle-and-thread grass has a positive and significant coefficient in the treated-sites response function, indicating that the more needle-and-thread grass before control, the larger the mean response observed from control. The opposite is found for thickspike wheatgrass, as the coefficient is negative and significant in explaining forage yield on the treated sites. The magnitudes of effects on forage yield, although opposite in sign, are similar according to the elasticity estimates for these two variables. Finally, forage-response functions for treated and untreated plots are nonlinear in time, as indicated by the significant (negative) sign on t^2. Negative t^2 implies that forage biomass initially increases over time in response to treatment but at a decreasing rate, and it will eventually decline if enough time passes. Note, however, that forage biomass had not yet reached pretreatment levels at the end of the study period for all abundance levels (Table 2). The elasticity estimates indicate similar magnitudes across the two equations for these trend-related variables. Overall, these regression results confirm the importance of environmental factors and site characteristics in explaining forage response from sagebrush control. Moreover, these results suggest that initial understory characteristics may very well impact economic outcomes of sagebrush control.

Economic Analysis

NPV of net revenues over the study period (1987–2004) range from a low of $-\$19.54 \cdot ha^{-1}$ to a high of $\$40.05 \cdot ha^{-1}$ depending on the initial sagebrush abundance level, response scenario analyzed, and assumed discount rate (Table 5). Based on actual forage response data, sagebrush control provides positive economic returns for sagebrush cover levels of 8% or higher regardless of the discount rate. The other response scenarios, however, generally do not indicate positive economic returns until sagebrush abundance is at 20% or 24%.

When comparing the average precipitation and soil moisture scenario to the actual forage-response scenario, it is interesting to note that economic returns across all sagebrush abundance levels are about half the returns for the actual forage-response data. One might expect that with average moisture conditions, total forage response should average out over the life of control, and therefore economic returns should not be that different from the observed. However, this is clearly not the case, and this result is largely because the NPV of those returns takes into account the magnitude of the economic return across the life of the investment. Figures 1 and 2 clearly indicate that precipitation and the resulting forage yields were above average during the first half of the study. When compared to the predicted net forage from the average moisture scenario, it is clear that the economic returns, which are discounted less heavily in the beginning of the control, are much higher for years 3 through 7 for the actual response data. This is largely a result of precipitation events over the study period. Moreover, this underscores the impact of variability in precipitation on the economic outcomes from sagebrush control. When examining the last years of the study, both forage response and precipitation are below average several times (Figs. 1 and 2).

The standard deviation of the economic returns for the predicted average moisture scenario indicates that variability is quite high relative to the average NPV across all the canopy cover levels for this scenario. This is related largely to sagebrush abundance but may also be related to understory characteristics. Note, for example, that the 28% abundance level barely has positive returns over the study period for the actual observed forage response. NPV is near breakeven at the

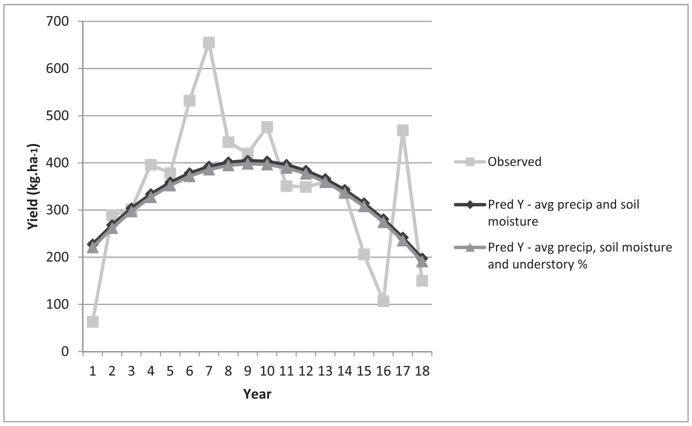

Figure 3. Observed yield difference versus predicted difference in forage biomass for average precipitation and soil moisture, as well as average understory percentage following sagebrush control, given pretreatment sagebrush cover of 24%.

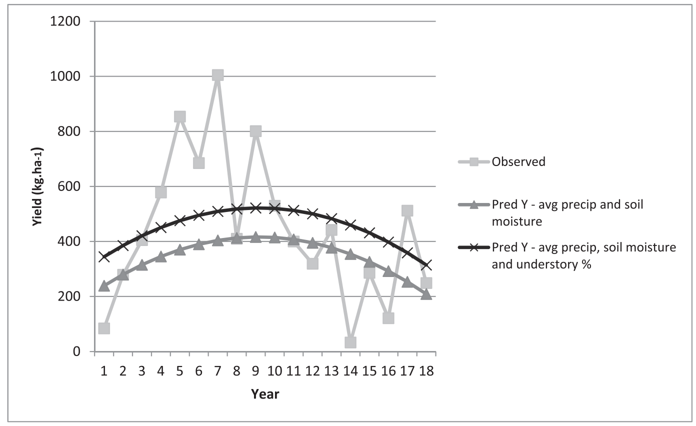

Figure 4. Observed yield difference versus predicted difference in forage biomass for average precipitation and soil moisture, as well as average understory percentage following sagebrush control, given pretreatment sagebrush cover of 40%.

4.67% discount rate and negative for the 6.67% discount rate in the average moisture scenario for 28% sagebrush abundance. This result is driven by the understory characteristics. The beginning percent of needle-and-thread grass is lowest for the 28% sagebrush abundance plots at 3.33% and well below the average across all plots of 19.63% (Table 1). Similar issues are observed for the 36% sagebrush cover level. The observed economic returns are nearly half the 32% level in the average moisture response scenario.

Results for the scenario incorporating average moisture and average understory characteristics offer additional insights. The estimated economic returns for this scenario indicate that sagebrush abundance level must be 20–24% depending on the discount rate before sagebrush control provides positive economic returns over the study period. The average economic returns across the abundance levels are nearly the same as those estimated in the average moisture scenario, but the returns are much more variable across the abundance levels according to the standard deviations for the two scenarios. This highlights the impact of beginning understory characteristics on the economic outcomes of sagebrush control. To further illustrate this point, when the 28% canopy level is assumed to have the average percent of needle-and-thread grass and thickspike wheatgrass initially, the predicted economic returns are much higher than those compared to the other scenarios, over $\$18 \cdot ha^{-1}$ or $\$12 \cdot ha^{-1}$ for the 4.67% and 6.67% discount rates, respectively. The effect of a higher percentage of needle-and-thread grass in the understory prior to control is to raise the mean forage response over the life of the control, thereby improving overall economic returns. Figures 3 and 4 illustrate this for the 24% and 40% sagebrush abundance levels. Figure 3 indicates that the predicted forage response for the average precipitation and soil moisture scenario is nearly the same as the predicted response for the scenario incorporating average understory percentages. Figure 4, however, indicates that the predicted forage response for the scenario incorporating average understory characteristics with average moisture conditions is much higher than the scenario for average precipitation and soil moisture alone. This is because the 40% site had 9.68% of needle-and-thread grass and 69.87% thickspike wheatgrass as compared to the 24% site, which had 25.85% needle-and-thread grass and 48.26% thickspike wheatgrass initially (Table 1).

DISCUSSION

Our specific research objective is to identify the economic threshold level at which sagebrush control is feasible. We use and report results from a unique long-term data set with yearly observations from a study area in the Northern Rocky Mountain region, across a broader range of sagebrush canopy covers, 4–40%, than have been reported in other studies. Our analyses indicate the variability across time and space associated with precipitation, sagebrush canopy cover, and beginning site understory characteristics greatly impacts the economic threshold level. Our results indicate the economic threshold level in the Northern Rocky Mountain region with similar species could vary between 8% and 24% depending on precipitation and site characteristics. This underscores the inherent risks range managers face when making decisions related to range improvements with the goal of increasing forage production.

Torell et al. (2005), in a study analyzing the impact of understory–overstory relationships on economic outcomes of brush control, found that optimal sagebrush canopy levels ranged between 6% and 14% for the sites they analyzed in New Mexico. Given our analysis of scenario 1, actual data including all variability in precipitation and across sites, it is interesting to note we conclude 8% canopy cover returned positive returns. While this canopy cover is similar to the Torell et al. (2005) study, further analysis of our results suggests this could in part be driven by the nature of the pattern of precipitation observed over the first years of our study period, which had higher-than-normal precipitation. Results from our analysis of scenario 2, assuming average precipitation and soil moisture conditions, indicate that the threshold sagebrush canopy cover would have been at least 20%. This suggests that the timing of precipitation can greatly impact the economic threshold of brush control.

These findings suggest a useful extension to this research. Specifically, results indicate that forage response to control is highly variable across time, in part because of variability in precipitation and soil moisture. This is highlighted by the comparison of scenarios 1 and 2 of our analyses, which indicates that average moisture conditions over the study period increased the sagebrush canopy cover at which positive economic returns occurred by 2.5 to 3 times. Because range managers cannot predict precipitation and soil moisture for future years, they face uncertainty about the magnitude of forage response to control and hence the magnitude of discounted net revenue from control. This uncertainty may increase the level of sagebrush abundance required for control to be economically justified as indicated in our average moisture scenario relative to actual observed data. Additional research that assesses threshold levels of infestation under uncertainty and the value of long-term weather forecasts (like those that relate El Niño/La Niña patterns to future precipitation patterns for some regions of the United States) could provide useful insights for range managers.

Our predicted NPVs are of similar magnitude as those reported by Torell et al. (2005), but given the nature of our study, we find a broader range of potential economic outcomes. Torell et al. (2005) report NPV of a single treatment across their study sites using estimated forage from their response function ranging from –$8.13 \cdot ha^{-1}$ to $40.32 \cdot ha^{-1}$ while we estimate potential economic returns ranging from –$19.54=ha^{-1}$ to $40.05=ha^{-1}$. Our broader range of economic outcomes highlights, in part, the broader range of sagebrush canopy covers analyzed in our study compared to that of Torell et al. (2005). That broader range of canopy cover, coupled with different species composition, precipitation patterns, and study period, explains these differences. It is also important to note that our estimates come from a generally shorter time horizon than those reported in Torell et al. (2005). Moreover, our assumed control costs are generally less given that 2–4,D is the chemical used.

Our results indicate that sagebrush had not yet reinvaded to pretreatment levels in all but one case. Moreover, ending forage production across treatment sites was above the untreated sites in all cases, suggesting that additional benefits from sagebrush control were possible but not captured in our analysis given that the study period was only 18 yr and life of control was likely beyond that. Thus, sagebrush abundance levels at which control becomes economically feasible could be below those reported here. Generally, our estimated economic returns indicate that the threshold level of sagebrush may be lower than that reported in Bastian et al. (1995), but their analysis only had 4 yr of response data for the same study area with which to predict returns.

A few limitations of the study should be noted. First, results are based on forage-response data collected in south-central Wyoming. Our results and that reported in the literature highlight that forage response to control likely differs across locations with significantly different site characteristics, such as forage species and understory composition. A second limitation of this study is that it considers only benefits and costs of big sagebrush control associated with livestock grazing. Range managers' objectives could involve other land uses and species, which would alter the benefits and costs of sagebrush control. As is noted in Torell et al. (2005), many such benefits and costs are difficult to empirically estimate.

IMPLICATIONS

We believe that this article contributes to the literature by analyzing forage yield across a broader range of canopy cover levels, ranging from 4% to 40%. We further investigate the impact of variability in precipitation and understory characteristics on economic outcomes of sagebrush control by analyzing three scenarios. Our results highlight the potentially broad range of economic threshold levels for sagebrush control that is impacted by pretreatment sagebrush abundance levels, environmental factors, and initial site characteristics, such as understory composition. We find that economic threshold levels of sagebrush canopy cover could vary between 8% and 24% for sites of similar species composition. Our analysis ultimately underscores the inherent risks associated with sagebrush control as illustrated in our predicted forage-response scenarios and estimated returns. When considering control, range managers must consider potential site characteristics that will give them the best chance of achieving positive economic outcomes as they relate to sagebrush abundance and understory composition. Moreover, range managers may want to consider long-range forecasts of precipitation in their decisions.

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LITERATURE CITED

AAEA Task Force on Commodity Costs and Returns. 2000. Commodity costs and returns estimation handbook. Ames, IA, USA: AAEA Task Force on Commodity Costs and Returns. p. 2–35, 2–38.

Alley, H. P., and D. W. Bohmont. 1958. Big sagebrush control. Laramie, WY, USA: Wyoming Agricultural Experiment Station. Bulletin 345. 5 p.

Barry, P., P. Ellinger, J. Hopkin, and C. B. Baker. 2000. Financial management in agriculture. Danville, IL, USA: Interstate Publishers. p. 249–343.

Bartlett, E. T., L. A. Torell, N. R. Rimbey, L. W. VanTassell, and D. W. McCollum. 2002. Valuing grazing use on public lands. *Journal of Range Management* 55:426–438.

Bartolome, J. W., and H. G. Heady. 1978. Ages of big sagebrush following sagebrush control. *Journal of Range Management* 31:403–411.

Bastian, C. T., J. J. Jacobs, and M. A. Smith. 1995. How much sagebrush is too much: an economic threshold analysis. *Journal of Range Management* 48:73–80.

Beetle, A. A. 1960. A study of sagebrush—section tridentatae of *Artemisia*. Laramie, WY, USA: Wyoming Agricultural Experiment Station. Bulletin 368. 83 p.

Blaisdell, J. P., R. B. Murray, and E. D. McArthur. 1982. Managing intermountain rangelands: sagebrush–grass ranges. Ogden, UT, USA: USDA Intermountain Forest and Range Experiment Station. General Technical Report INT-134. 43 p.

Bureau of Labor Statistics. 2008. Producer price index—all-farm products. Available at: http://data.bls.gov/cgi-bin/dsrv. Accessed 27 April 2008.

Dean, S. K. 1983. Plant response to livestock grazing and big sagebrush chemical control in western Wyoming 1962–1980 [thesis]. Laramie, WY, USA: University of Wyoming. 96 p.

Freeburn, J. W. 1979. An economic analysis of sagebrush spraying in Wyoming, 1952–1976 [thesis]. Laramie, WY, USA: University of Wyoming. 115 p.

Hedrick, D. W., D. N. Hyder, F. A. Sneva, and C. E. Poulton. 1966. Ecological response of sagebrush–grass range in central Oregon to mechanical and chemical removal of *Artemisia*. *Ecology* 47(3):432–439.

Johnson, J. R., and G. F. Payne. 1968. Sagebrush reinvasion as affected by some environmental influences. *Journal of Range Management* 21(4):209–213.

Johnson, W. M. 1969. Life expectancy of a sagebrush control in central Wyoming. *Journal of Range Management* 22:177–182.

Kearl, W. G. 1965. A survey of big sagebrush control in Wyoming, 1952–64. Laramie, WY, USA: Wyoming Agricultural Experiment Station. Bulletin 217. 42 p.

Krenz, R. D. 1962. Costs and returns from spraying sagebrush with 2,4-D. Laramie, WY, USA: Wyoming Agricultural Experiment Station. Bulletin 390. 31 p.

Lauenroth, W. K., and W. C. Whitman. 1977. Dynamics of dry matter production in a mixed-grass prairie in western North Dakota. *Oecologia* 27(4):339–351.

Maier, A. M., B. L. Perryman, R. A. Olson, and A. L. Hild. 2001. Climatic influences on recruitment of 3 subspecies of *Artemisia tridentata*. *Journal of Range Management* 54(6):699–703.

McDaniel, K. C., D. L. Anderson, and J. F. Balliette. 1991. Wyoming big sagebrush control with metsulfuron and 2,4-D in northern New Mexico. *Journal of Range Management* 44(6):623–627.

McDaniel, K. C., D. L. Anderson, and L. A. Torell. 1992. Vegetation change following big sagebrush control with tebuthiuron. Las Cruces, NM, USA: New Mexico State University Agricultural Experiment Station. Bulletin 764. 41 p.

McDaniel, K. C., and J. F. Balliette. 1986. Control of big sagebrush (*Artemisia tridentata*) with pelleted tebuthiuron. *Weed Science* 34:276–280.

McDaniel, K. C., L. A. Torell, and C. G. Ochoa. 2005. Wyoming big sagebrush recovery and understory response with tebuthiuron control. *Rangeland Ecology & Management* 58:65–76.

Mendelsohn, B. J. 2010. Factors affecting big sagebrush cover in southwest Montana [thesis]. Bozeman, MT, USA: Montana State University. 85 p.

Mueggler, W. F., and J. P. Blaisdell. 1958. Effect on associated species of burning, roto-beating, spraying and railing sagebrush. *Journal of Range Management* 11:61–66.

National Agricultural Statistics Service for Wyoming Agricultural Statistics. 2008. Available at: http://www.nass.usda.gov/wy. Accessed 23 March 2008.

National Applied Resources Sciences Center. 1996. Sampling vegetation attributes. Devner, CO, USA: US Department of the Interior–Bureau of Land Management. BLM/RS/ST-96/002+1730. 163 p.

Parks, R. W. 1967. Efficient estimation of a system of regression equations when disturbances are both serially and contemporaneously correlated. *Journal of the American Statistical Association* 62:500–509.

SAS. 2009. The TSCSREG procedure/Parks method (autoregressive model). *SAS OnlineDoc 9.1.3*. Available at: http://support.sas.com/onlinedoc/913/docMainpage.jsp. Accessed 20 June 2009.

Scarnecchia, D. L., and M. M. Kothmann. 1982. A dynamic approach to grazing management terminology. *Journal of Range Management* 35:262–264.

Schmisseur, E. 1981. Spraying big sagebrush range in eastern Oregon: management insights. Corvallis, OR, USA: Oregon State University Extension Service. Special Report 638. 11 p.

Smith, M. A., T. L. Thurow, and D. L. Legg. 2005. Report for 2002WY7B: drought prediction model development and dissemination in Wyoming. Available at: http://water.usgs.gov/wrri/04grants/Progress%20Completion%20Reports/2002WY7B.pdf. Accessed 14 November 2011.

Society for Range Management. 1974. A glossary of terms used in range management 2nd ed. M. M. Kothmann [ed.]. Denver, CO, USA: Society for Range Management. 36 p.

Sonder, L. W., and H. P. Alley. 1961. Soil-moisture retention and snow-holding capacity as affected by the chemical control of big sagebrush (*Artemisia tridentata* Nutt.). *Weeds* 9(1):27–35.

Sturges, D. L. 1977. Snow accumulation and melt in sprayed and undisturbed big sagebrush vegetation. Fort Collins, CO, USA: USDA, Forest Service Rocky Mountain Forest and Range Experiment Station. Research Note RM-348. 6 p.

Sturges, D. L. 1986. Responses of vegetation and ground cover to spraying a high elevation, big sagebrush watershed with 2,4-D. *Journal of Range Management* 39:141–146.

Tanaka, J. A., and J. P. Workman. 1988. Economic optimum big sagebrush control for increasing crested wheatgrass production. *Journal of Range Management* 41:172–177.

Torell, L. A., K. C. McDaniel, and V. Koren. 2011. Estimating grass yield on blue grama range from seasonal rainfall and soil moisture. *Rangeland Ecology & Management* 64:56–66.

Torell, L. A., K. C. McDaniel, and C. G. Ochoa. 2005. Economics and optimal frequency of Wyoming big sagebrush control with tebuthiuron. *Rangeland Ecology & Management* 58:77–84.

US Government Printing Office. 2007. Economic report of the president. Available at: http://www.gpoaccess.gov/eop/tables07.html. Accessed 28 August 2009.

Wambolt, C. L., and G. F. Payne. 1986. An 18-yr comparison of control methods for Wyoming big sagebrush in southwestern Montana. *Journal of Range Management* 39:314–319.

Watts, M. J., and C. L. Wambolt. 1989. Economic evaluation of Wyoming big sagebrush (*Artemisia tridentata*) control methods. *Weed Technology* 3:640–645.