Evaluating the Economic Efficiency of Wildfire Fuel Reduction Treatments in Sagebrush Ecosystems that Vary in Ecological Resilience and Invasion Resistance

Thomas Bridges-Lyman, Michael H. Taylor

University of Nevada, Reno

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Introduction

Ecology and management of sagebrush ecosystems

Figure: Sagebrush association in central Nevada

Introduction

Ecology and management of sagebrush ecosystems

- Sagebrush ecosystems are deteriorating rapidly:
  - As of 2020, only 33 million acres (13.6%) of the sagebrush biome fall into the highest tier of ecological integrity, decreasing at a rate of almost 1 million acres per year (Doherty et al., 2022)
  - Nearly 20% of the Great Basin is dominated by invasive annual grasses (Smith et al., 2022)
- Two major ecological threats exacerbate fire risk:
  - Invasive exotic annual grasses associated with more frequent fire (Whisenant, 1990; Balch et al., 2013)
  - Pinyon-juniper ("PJ") expansion associated with fires of higher intensity and severity (Miller et al., 2013)

Introduction

Ecology and management of sagebrush ecosystems

- Land managers can preserve sagebrush ecosystems and manage fire risk through fuel reduction treatments
- The dominant treatment paradigm in sagebrush ecosystems applies the concepts of **ecological resilience** (Holling, 1973) and **resistance to invasion** (Folke et al., 2004)
- Chambers et al. (2023) assigned recommended fuel reduction treatments to different combinations of dominant sage association, RSL, and RST, known as **treatment response groups (TRGs)**

Introduction

Economics of fuel treatments

- The abiotic factors that inform R+R also affect ecological dynamics and may alter the paths of benefits and costs over time
- Benefits of fuel treatments play out over time:
  - Epanchin-Niell et al. (2009): Post-fire revegetation in sagebrush
  - Houtman et al. (2013): Suppression vs. let burn
  - Taylor et al. (2013): Suppression costs in sagebrush
  - Taylor et al. (2015): Ecological restoration and fuel reduction in ponderosa pine forests

Overview

Questions:

1. To what extent do benefit-cost ratios vary with R&R?
2. Do indicators of resilience and resistance align with economic efficiency?
3. What ecological and economic parameters drive differences in the efficiency of treatment between R&R categories?

Overview

Approach:

1. Develop generalized models of sagebrush communities and parameterize specific to R+R
   - LANDFIRE Biophysical Setting (BpS) descriptions
   - Rangeland Analyis Platform (RAP; Allred et al., 2021)
   - Monitoring Trends in Burn Severity (MTBS; Eidenshink et al., 2007)
2. Simulate ecological dynamics over 100-year management horizons under treatment and non-treatment scenarios
3. Assess wildfire suppression cost savings and other greater public benefits across treatment and non-treatment scenarios to derive benefit-cost ratios

Contributions:

1. Incorporate ecological resilience and resistance to invasion into benefit cost analysis of fuel treatments
2. Parameterize models of sagebrush communities using observational data

Methods and Materials

Simulation

- Simulation code written in R, adapted from Taylor et al. (2015)
- For each treatment response group (dominant sage association/RSL/RST), we perform 10000 runs of treatment and non-treatment scenarios
- Each simulation begins in a treatable model phase and lasts for 100 years
- In each year, we consider four following events in the following order:
  1. Wildfire
  2. Treatment
  3. Ecological succession
  4. Annual grass invasion
- Assess economic benefits by comparing treatment and non-treatment scenarios:

$$\Delta NPV = \frac{1}{10000} \sum_{m=1}^{10000} \left[\sum_{t=1}^{100} \frac{1}{(1+r)^{t-1}} V\left(s_{mt}^{TREAT}\right) - \sum_{t=1}^{100} \frac{1}{(1+r)^{t-1}} V\left(s_{mt}^{NO\ TREAT}\right) \right]$$

Methods and Materials

Study region and treatment response groups

- Snake River Plain, Central Basin and Range, and Northern Basin and Range EPA Level III Ecoregions
- Three sagebrush associations of interest:
  - Mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*)
  - Black sagebrush (*Artemisia nova*)
  - Low sagebrush (*Artemisia arbuscula*)
- For each sagebrush type, we selected three R+R categories with the highest area as computed by Chambers et al. (2023)

Dominant sagebrush association	RSL	RST	Area of TRG (sq. km)
Mountain big sagebrush	M	M	12266
Mountain big sagebrush	H+MH	H+MH	6491
Mountain big sagebrush	M	ML	3455
Black sagebrush	ML	ML	1804
Black sagebrush	M	ML	559
Black sagebrush	M	M	418
Low sagebrush	M	M	1521
Low sagebrush	ML	ML	504
Low sagebrush	ML	M	416

Table: Modeled TRGs in our study

Methods and Materials

Ecological model

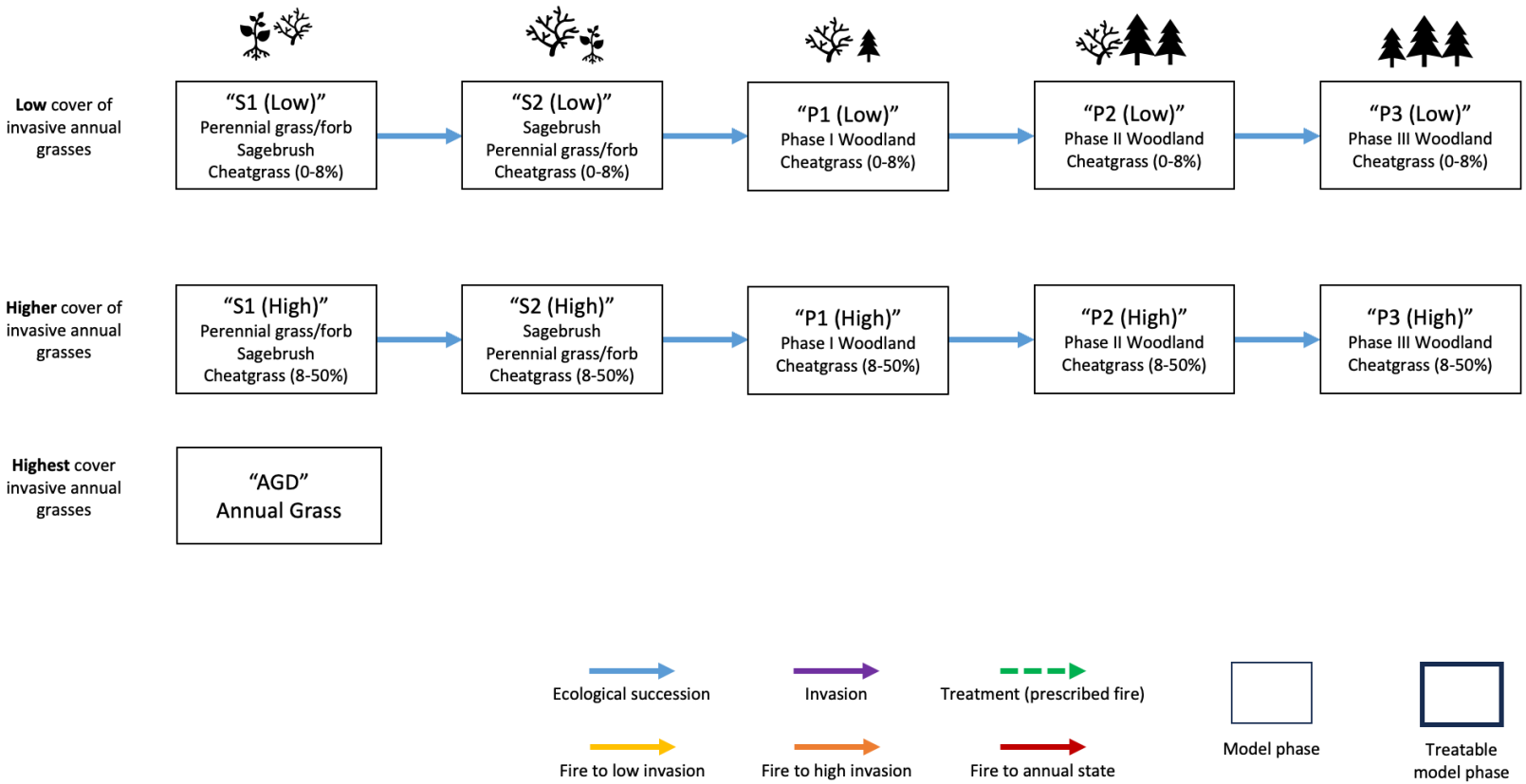

Figure: Generalized model for mountain big sagebrush

Methods and Materials

Ecological model

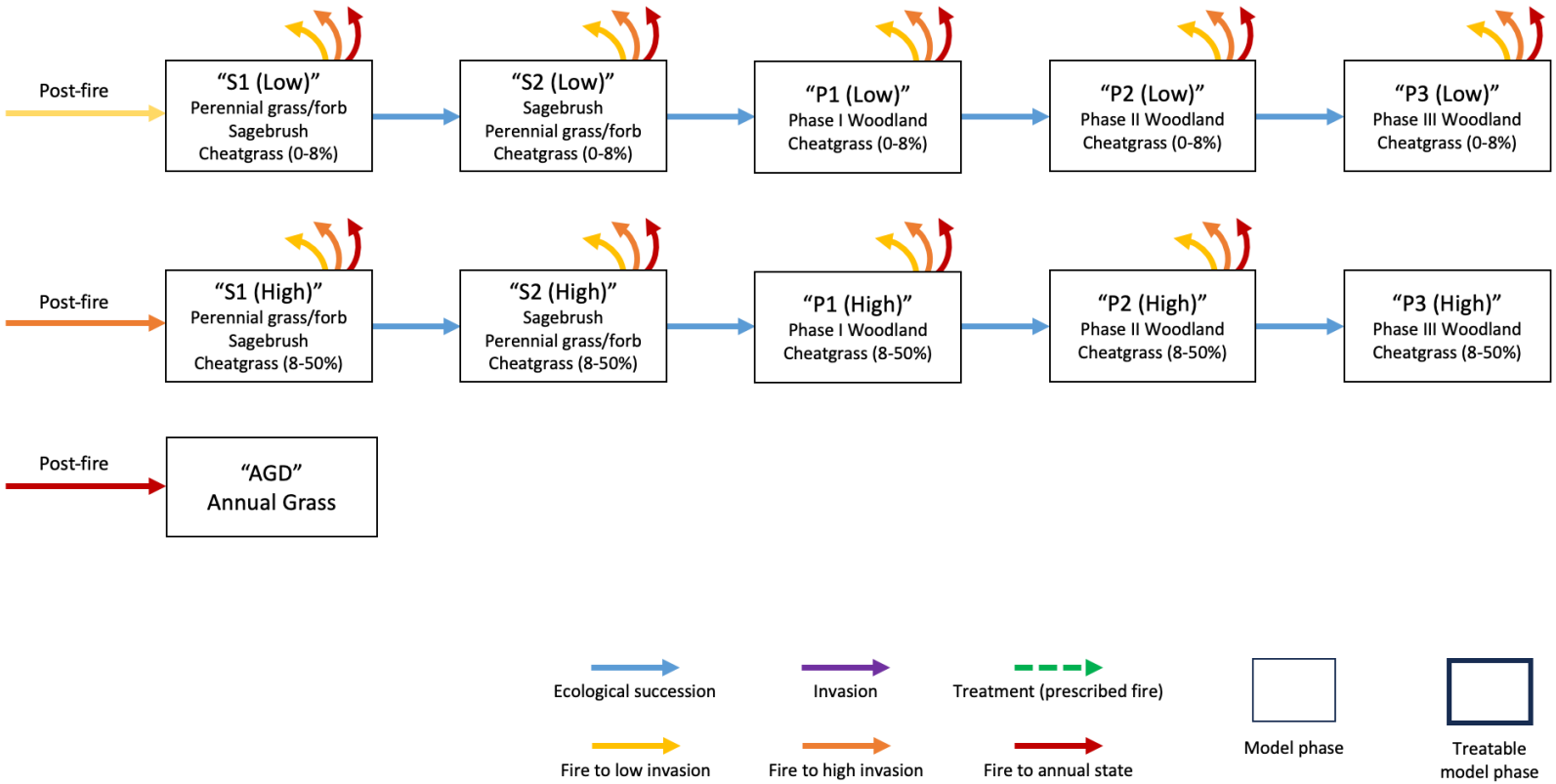

Figure: Generalized model for mountain big sagebrush

Methods and Materials

Ecological model

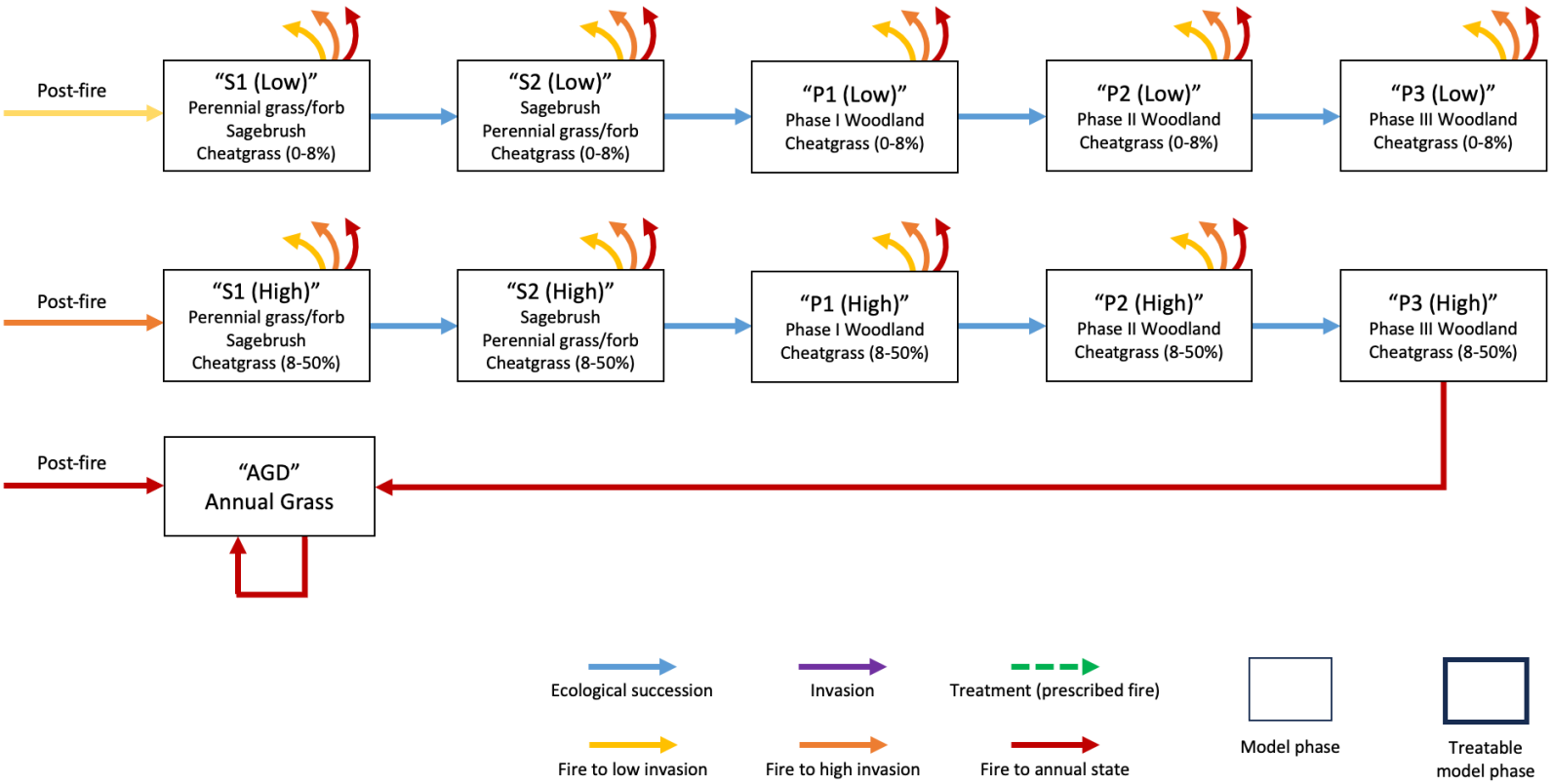

Figure: Generalized model for mountain big sagebrush

Methods and Materials

Ecological model

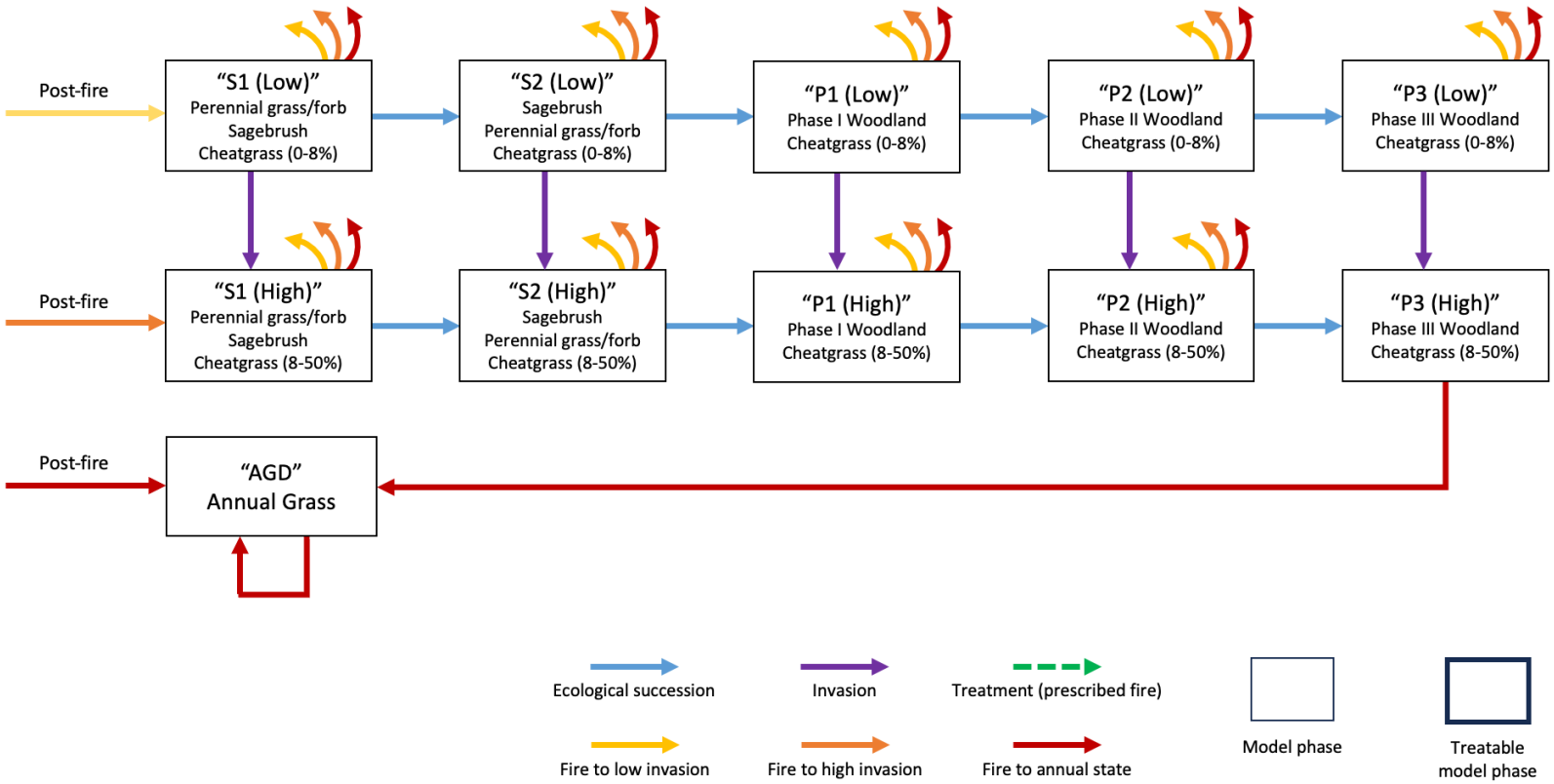

Figure: Generalized model for mountain big sagebrush

Methods and Materials

Ecological model

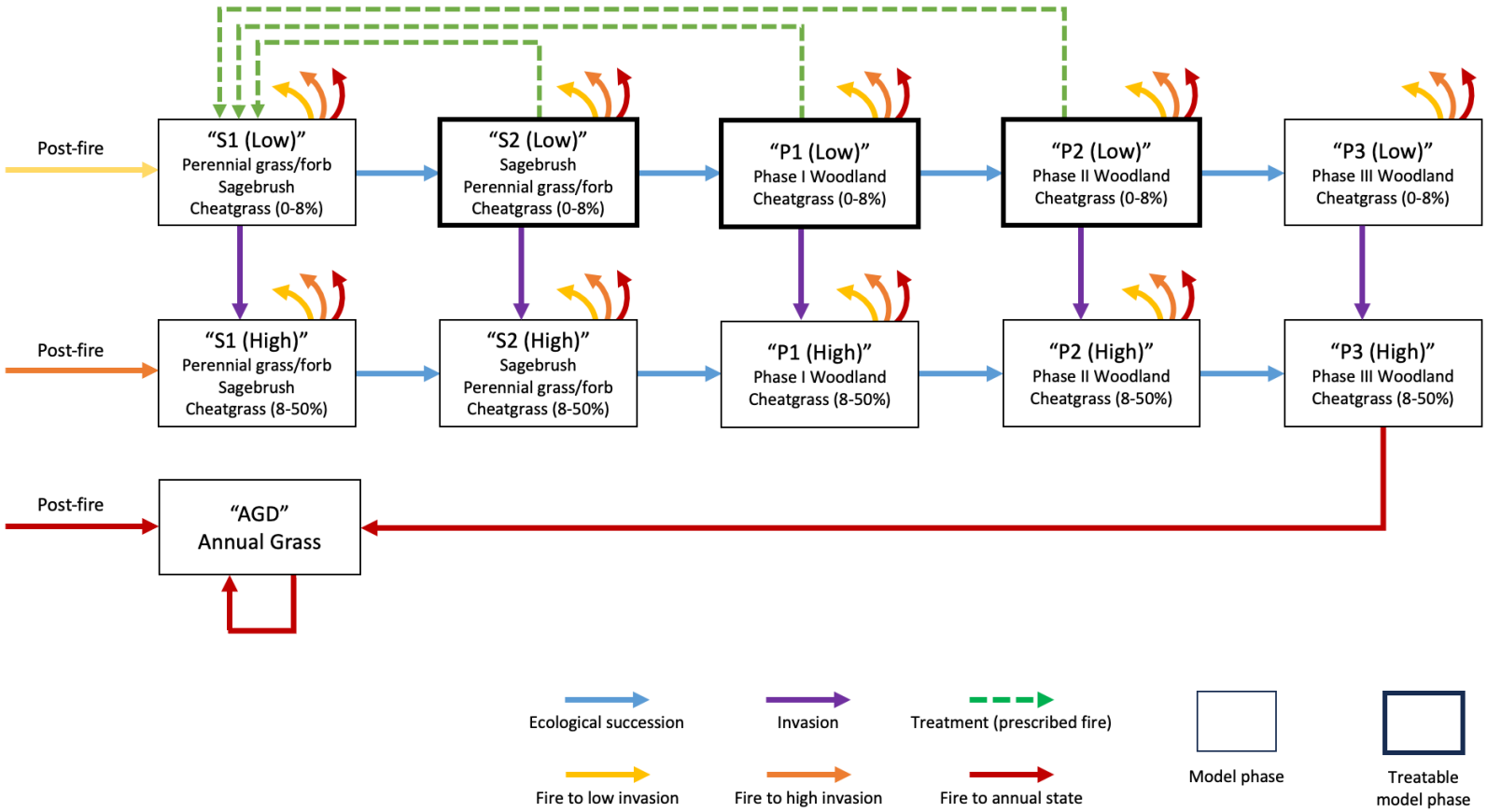

Figure: Generalized model for mountain big sagebrush

Methods and Materials

Ecological model

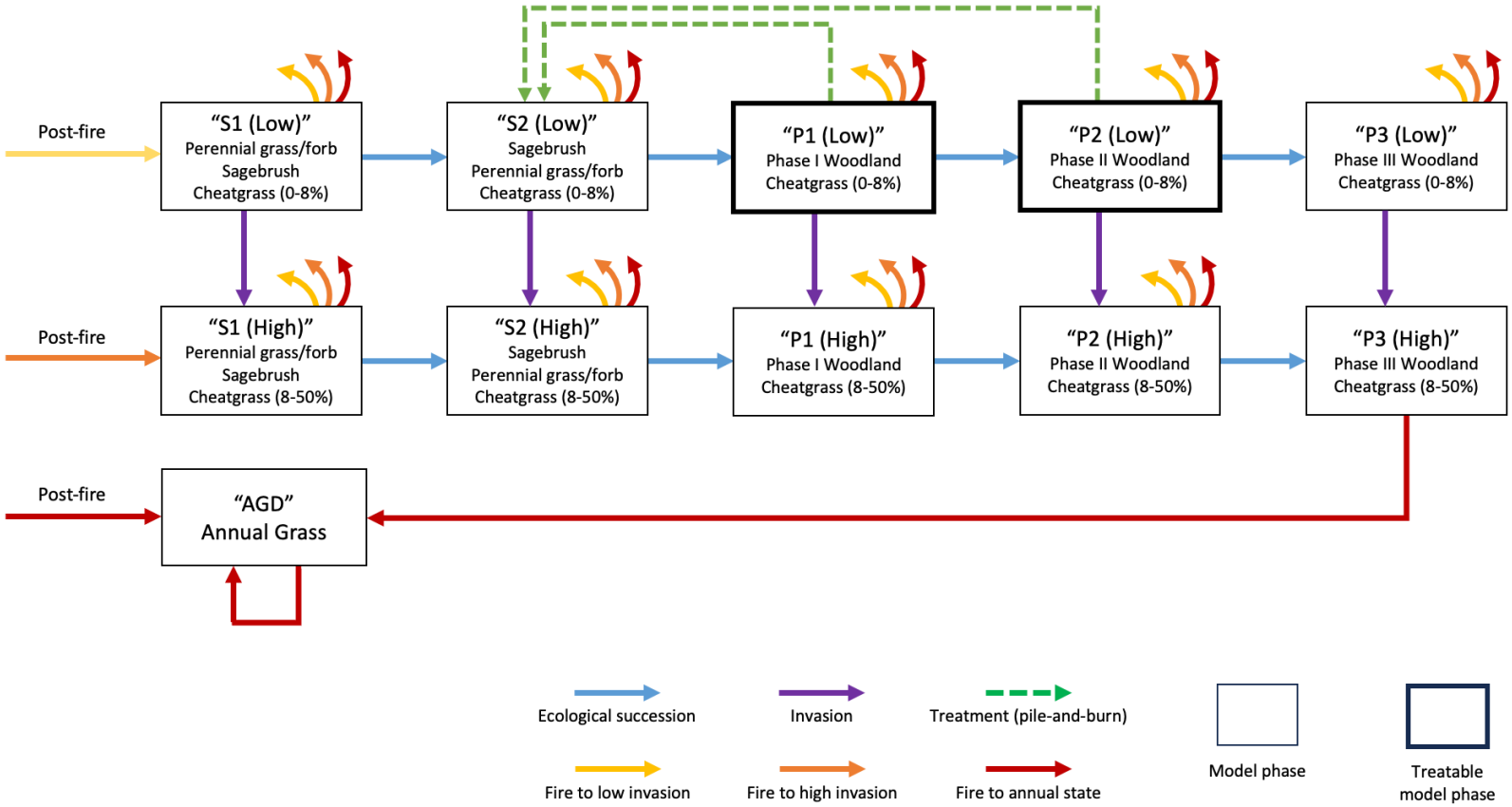

Figure: Generalized model for black sagebrush and low sagebrush

Ecological succession times:

- For M/M with low invasion, use deterministic succession times from LANDFIRE Biophysical Setting (BpS) descriptions of reference ecosystems
- Use expert opinion to modify succession times to other R&R categories in low succession
- Increase succession times by a factor for high invasion condition

Dominant sagebrush association	RSL	RST	Low S1 to S2	Low S2 to P1	Low P1 to P2	Low P2 to P3	Invaded Multiplier
Mountain big sagebrush	H+MH	H+MH	20	50	45	51	1x
Mountain big sagebrush	M	M	12	38	30	45	1.5x
Mountain big sagebrush	M	ML	15	45	40	51	2x

Table: Ecological succession times (years) between model phases by TRG

Methods and Materials

Parameterization

Parameterization regions:

- Use TRG data from Chambers et al. (2023) to identify woodland phases in 2020
- Use five-year means of remotely sensed cover data from Rangeland Analysis Platform (Allred et al., 2021) to assess level of cheatgrass and to identify model phase
- Use Monitoring Trends in Burn Severity (Eidenshink et al., 2007) to identify burn areas and type of burn

Yearly probability of invasion:

- Identify regions corresponding to each low invasion model phase in 1990
- Identify subregions that do not experience a burn between 1986 and 2020
- Compute percentages of initial regions that have converted to higher tiers of invasion
- Under an assumption of time invariant yearly probabilities, use geometric distribution CDF to estimate the annual probability of conversion

Methods and Materials

Parameterization

Yearly burn probabilities:

- Assume the current distribution of burn probabilities across each parameterization region reflects (1) long-term burn probabilities and (2) distribution of burn probabilities within a single phase over time
- Over each model phase region, take mean of burn probabilities from FSim burn probability output product calibrated to Great Basin (Short et al., 2023)

Post-fire transition probabilities:

- Identify regions corresponding to all model phases in 1990
- Identify subregions that experience a single burn between 1991 and 2005
- Identify subregions that have ten years of recovery (i.e., no burn)
- Compute percentage conversion rates to each tier of invasion, and use as conditional fire transition probabilities

Methods and Materials

Costs of treatment

- Treatment type and schedule from Chambers et al. (2023):
  - Prescribed burn for mountain big sagebrush
  - Cut-and-remove for black sagebrush and low sagebrush
- Treatment costs using current Environmental Quality Incentives Program (EQIP) unit costs associated with prescribed fire and mechanical treatments (NRCS 2023)

Dominant sage association	Treatment type	EQIP practice	EQIP component	Cost per acre
Mountain big sagebrush	Prescribed fire	Prescribed Burning	Steep Terrain, Volatile or Woody Fuels	$16.58
Black and low sagebrush	Pile-and-burn	Prescribed Burning	Pile or Windrow Burning	$275.47

Methods and Materials

Benefits of treatment

Wildfire suppression costs:

- Use USFS fire expenditure data from 1995-2013
- Adjust for inflation using Government Consumption Expenditures and Gross Investment (federal, non-defense) price index
- Randomly sample per-acre fire costs from USFS fire expenditure data with appropriate NFDRS fuel model, weighted by fire sizes

Greater benefits of PJ removal:

- Cornachione et al. (2023) used benefit transfer to derive economic benefits of pinyon-juniper removal associated with habitat, recreation/hunting, and water availability

Results and Discussion

Mountain big sagebrush

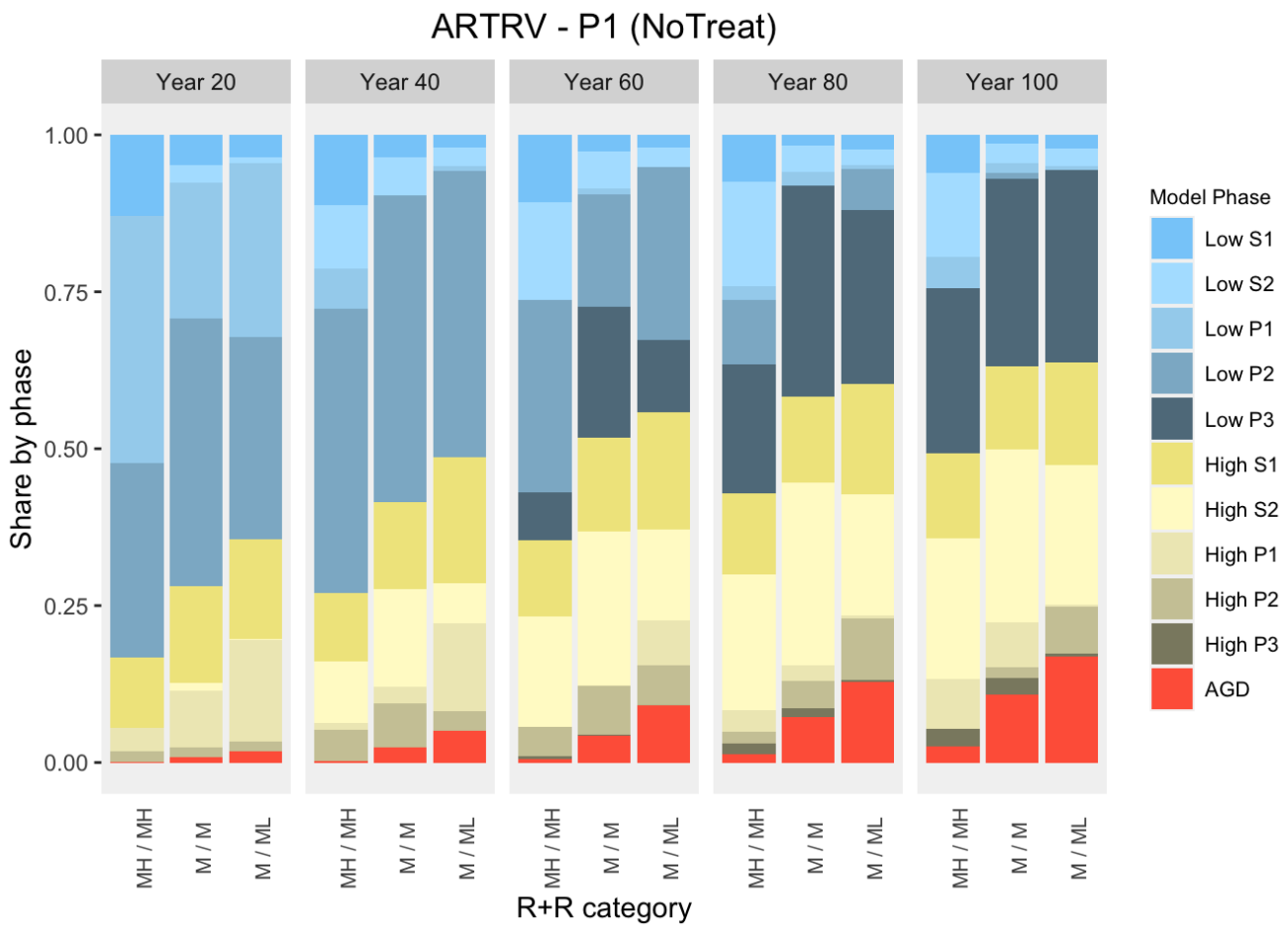

Figure: Ecological outcomes for mountain big sagebrush without treatment

Results and Discussion

Mountain big sagebrush

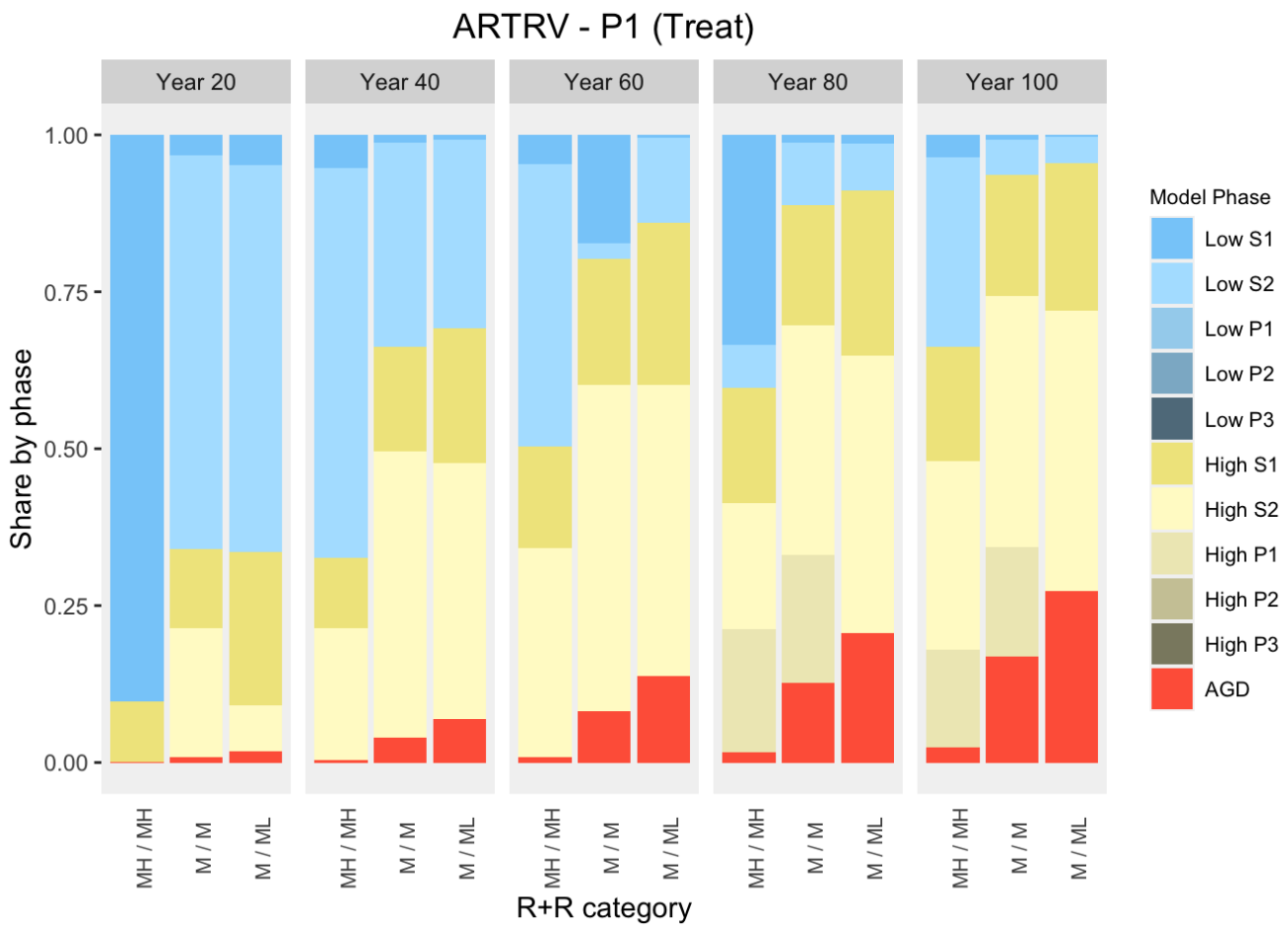

Figure: Ecological outcomes for mountain big sagebrush with treatment

Results and Discussion

Mountain big sagebrush

Initial model phase		S2			P1			P2	
RSL/RST	MH/MH	M/M	M/ML	MH/MH	M/M	M/ML	MH/MH	M/M	M/ML
No Treat: % final phase: low	0.35	0.17	0.11	0.50	0.37	0.36	0.68	0.57	0.60
No Treat: % final phase: high	0.63	0.68	0.62	0.47	0.52	0.47	0.30	0.35	0.31
No Treat: % final phase: annual state	0.02	0.16	0.27	0.03	0.11	0.17	0.02	0.08	0.10
No Treat: % final phase: sagebrush (S1-S2)	0.63	0.55	0.51	0.55	0.45	0.44	0.44	0.33	0.31
No Treat: % final phase: woodland (P1-P3)	0.35	0.30	0.23	0.42	0.44	0.39	0.55	0.59	0.59
No Treat: Mean total number of wildfires	1.29	1.64	1.61	1.22	1.38	1.28	0.93	0.96	0.79
Treat: % final phase: low	0.33	0.06	0.04	0.33	0.06	0.04	0.34	0.06	0.04
Treat: % final phase: high	0.64	0.77	0.68	0.64	0.77	0.68	0.64	0.77	0.68
Treat: % final phase: annual state	0.02	0.17	0.28	0.02	0.17	0.28	0.02	0.17	0.27
Treat: % final phase: sagebrush (S1-S2)	0.82	0.65	0.72	0.82	0.66	0.72	0.82	0.66	0.73
Treat: % final phase: woodland (P1-P3)	0.16	0.17	0.00	0.16	0.17	0.00	0.16	0.17	0.00
Treat: Mean total number of wildfires	0.97	1.59	1.54	0.97	1.58	1.54	0.96	1.58	1.52

Table: Ecological outcomes for mountain big sagebrush simulations

Results and Discussion

Mountain big sagebrush

Initial model state	P1			P2		
RSL/RST	MH/MH	M/M	M/ML	MH/MH	M/M	M/ML
No Treat: Mean cost of wildfire suppression ($)	209.11	212.10	208.31	183.04	161.64	131.32
Treat: Mean cost of wildfire suppression ($)	42.61	86.43	82.86	39.18	81.07	75.07
Treat: Mean wildfire suppression cost savings ($)	166.50	125.67	125.45	143.86	80.57	56.25
Treat: Mean PJ removal benefits ($)	103.91	85.91	82.97	109.63	92.17	91.46
Treat: Mean combined benefits ($)	270.41	211.58	208.41	253.49	172.74	147.71
Treat: Mean number of treatments	1.32	1.19	1.10	1.32	1.20	1.12
Treat: Mean cost of treatment ($)	17.01	17.05	16.66	17.02	17.14	16.82
Treat: Mean benefit-cost ratio (wildfire costs only)	9.79	7.37	7.53	8.45	4.70	3.35
Treat: Mean benefit-cost ratio (total benefits)	15.90	12.41	12.51	14.90	10.08	8.78

Table: Economic outcomes for mountain big sagebrush simulations

Results and Discussion

Mountain big sagebrush

Initial model state	P1			P2		
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Treat: Mean benefit-cost ratio (total benefits)	15.90	12.41	12.51	14.90	10.08	8.78

Table: Economic outcomes for mountain big sagebrush simulations

Results and Discussion

Black sagebrush

Initial model phase	P1			P2		
RSL/RST	M/M	M/ML	ML/ML	M/M	M/ML	ML/ML
No Treat: % final phase: low	0.49	0.41	0.40	0.68	0.66	0.58
No Treat: % final phase: annual	0.15	0.19	0.21	0.10	0.14	0.19
Treat: % final phase: low	0.07	0.04	0.08	0.07	0.04	0.08
Treat: % final phase: annual	0.35	0.46	0.42	0.35	0.46	0.42
No Treat: Mean cost of wildfire suppression ($)	137.42	98.54	105.81	118.63	105.47	139.76
Treat: Mean cost of wildfire suppression ($)	43.06	32.38	30.47	40.90	31.28	30.13
Treat: Mean wildfire suppression cost savings ($)	94.36	66.16	75.34	77.73	74.19	109.63
Treat: Mean benefit-cost ratio (wildfire costs only)	0.34	0.24	0.28	0.28	0.27	0.40

Table: Economic and ecological outcomes for black sagebrush simulations

Results and Discussion

Black sagebrush

Initial model phase	P1			P2		
RSL/RST	M/M	M/ML	ML/ML	M/M	M/ML	ML/ML
No Treat: % final phase: low	0.49	0.41	0.40	0.68	0.66	0.58
No Treat: % final phase: annual	0.15	0.19	0.21	0.10	0.14	0.19
Treat: % final phase: low	0.07	0.04	0.08	0.07	0.04	0.08
Treat: % final phase: annual	0.35	0.46	0.42	0.35	0.46	0.42
No Treat: Mean per-acre cost of wildfire suppression ($)	137.42	98.54	105.81	118.63	105.47	139.76
Treat: Mean per-acre cost of wildfire suppression ($)	43.06	32.38	30.47	40.90	31.28	30.13
Treat: Mean wildfire suppression cost savings ($)	94.36	66.16	75.34	77.73	74.19	109.63
Treat: Mean benefit-cost ratio (wildfire costs only)	0.34	0.24	0.28	0.28	0.27	0.40

Table: Economic and ecological outcome statistics for 100-year simulations of black sagebrush

Conclusions

- Treatment decreases wildfire suppression costs across all models
- Benefit-cost ratios vary with R+R and with pre-treatment phase
- Economic efficiency sometimes aligns with R+R indicators
- Model results convey tradeoff between PJ expansion and annual grass invasion

Acknowledgments

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Comments/questions/suggestions?
thomasbl@nevada.unr.edu

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Invasion Parameters

Sage type	RSL	RST	S1	S2	P1	P2	P3
Mountain big sagebrush	H+MH	H+MH	0.004	0.012	0.005	0.001	0.000
Mountain big sagebrush	M	M	0.010	0.027	0.012	0.002	0.001
Mountain big sagebrush	M	ML	0.014	0.032	0.018	0.002	0.000
Black sagebrush	M	M	0.007	0.026	0.008	0.002	0.001
Black sagebrush	M	ML	0.015	0.028	0.014	0.002	0.000
Black sagebrush	ML	ML	0.011	0.022	0.011	0.002	0.001
Low sagebrush	M	M	0.006	0.026	0.010	0.003	0.001
Low sagebrush	ML	M	0.003	0.033	0.012	0.002	0.000
Low sagebrush	ML	ML	0.010	0.016	0.013	0.004	0.001

Table: Yearly probability of transition from low invasion to high invasion by TRG and model phase