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Authors: Cruz, Michelle P. Dela, Beauchamp, Vanessa B., Shafroth, Patrick B., Decker, Cheryl, and O'Neil, Aviva

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CONSERVATION ISSUES

Adaptive Restoration of River Terrace Vegetation through Iterative Experiments

Michelle P. Dela Cruz[1]

[1]BIA Southwest Regional Office
1001 Indian School Road NW
Albuquerque, NM 87104

Vanessa B. Beauchamp[2,6]
Patrick B. Shafroth[3]
Cheryl Decker[4]
Aviva O'Neil[5]

[2]ASRC Management Services contracted to
USGS Fort Collins Science Center
2150 Centre Ave, Bldg C
Fort Collins, CO 80526

[3]U.S. Geological Survey
Fort Collins Science Center
2150 Centre Ave, Bldg C
Fort Collins, CO 80526

[4]National Park Service
Southeast Utah Group
2282 S. West Resource Blvd.
Moab, UT 84532

[5]Zion National Park
State Route 9
Springdale, UT 84767

[6] Corresponding author:
vbeauchamp@towson.edu; Phone: 410-704-2286; Fax: 410-704-2405
Current address:
Towson University, Department of Biological Sciences, Towson MD 21252

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ABSTRACT: Restoration projects can involve a high degree of uncertainty and risk, which can ultimately result in failure. An adaptive restoration approach can reduce uncertainty through controlled, replicated experiments designed to test specific hypotheses and alternative management approaches. Key components of adaptive restoration include willingness of project managers to accept the risk inherent in experimentation, interest of researchers, availability of funding for experimentation and monitoring, and ability to restore sites as iterative experiments where results from early efforts can inform the design of later phases. This paper highlights an ongoing adaptive restoration project at Zion National Park (ZNP), aimed at reducing the cover of exotic annual *Bromus* on riparian terraces, and revegetating these areas with native plant species. Rather than using a trial-and-error approach, ZNP staff partnered with academic, government, and private-sector collaborators to conduct small-scale experiments to explicitly address uncertainties concerning biomass removal of annual bromes, herbicide application rates and timing, and effective seeding methods for native species. Adaptive restoration has succeeded at ZNP because managers accept the risk inherent in experimentation and ZNP personnel are committed to continue these projects over a several-year period. Techniques that result in exotic annual *Bromus* removal and restoration of native plant species at ZNP can be used as a starting point for adaptive restoration projects elsewhere in the region.

Index terms: adaptive restoration, *Bromus*, imazapic, revegetation, riparian

INTRODUCTION

Ecological restoration by trial and error can be risky, inefficient, and expensive, particularly for large projects or when significant uncertainties about the site or ecosystem are present (Bormann et al. 2007; Taylor and Short 2009). Many trial and error approaches are based on intuition and knowledge of managers, which can be an important part of the restoration process (Nature Editorial 2007). However, this approach does not provide a way to test cause and effect relationships between management practices and ecosystem responses (Lee 1993; Schreiber et al. 2004; Zedler 2005; Dettman and Mabry 2008). Results from trial and error approaches only allow for speculation about the causes of success or failure and may only afford a limited ability to predict the outcome of future restoration attempts (Zedler 2005).

Adaptive restoration is an alternative approach that begins by recognizing key uncertainties at the initiation of the restoration planning process and addresses them by designing projects as field experiments to test hypotheses and compare the effects of different management actions (Lee 1993; Elzinga et al. 2001). Adaptive restoration is similar to active adaptive management in that both focus on explicitly planned experiments that are designed to inform subsequent management actions. In adaptive management, a management strategy and monitoring program are implemented at the outset, using the best available information. Data are gathered and experiments are developed when ecosystem responses highlight additional research needs (Lee 1993; Elzinga et al. 2001). Results from experiments are used in an iterative manner to continually adjust management practices. In adaptive restoration, key knowledge gaps are clear in advance and experimentation is designed into the project at the outset. In adaptive restoration, the project site is divided into replicate subareas where different treatments are applied or different management actions are compared. This approach allows for statistically robust experiments where cause and effect can be determined and ineffective strategies ruled out (Zedler and Callaway 2003; Zedler 2005, 2006). In the short term, this process can be conducted as a series of small modules at a particular site, where results from earlier phases can inform later experiments and subsequent projects (Zedler 2005). In the long term, this experiment-focused, phased approach allows scientists and restoration practitioners to accumulate knowledge that can be applied to a range of restoration contexts and objectives (Lee 1993).

In this paper, we describe an ongoing adaptive restoration process at Zion National Park (ZNP), in the southwestern United States. Restoration efforts on riparian terraces dominated by exotic annual bromes (*Bromus tectorum* L. and *Bromus diandrus* Roth.; hereafter referred to collectively as

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bromes) are considered a high priority in ZNP. These grasses were first introduced to ZNP and the western United States in the late 1800s and have since spread throughout much of the western United States, where they occupy an estimated 8.9 million ha (Brooks et al. 2004; Sperry et al. 2006). Bromes gain a competitive advantage by germinating in the fall with the arrival of cool moisture and resuming growth early in the spring before most natives germinate or emerge (Harris 1967; Rafferty and Young 2002). Reduced plant biodiversity, altered nutrient cycles (Brooks et al. 2004; Sperry et al. 2006), and increased fire frequency (Brooks et al. 2004) are common consequences of brome invasion. Issues associated with exotic bromes may be most germane to the western United States; however, the effect of alien grass species on biodiversity and ecosystem functioning is becoming increasingly important at a global level (D'Antonio and Vitousek 1992).

Preliminary planning exercises for restoration activities on riparian terraces along the North Fork of the Virgin River (NFVR) highlighted many uncertainties surrounding control of exotic annual bromes and revegetation with native xeroriparian plant species. Staff at ZNP decided to confront some of these uncertainties with a program of small-scale experiments. We describe the information gained from these projects and their impact on subsequent project phases in the context of best management practices for restoration at ZNP (Figure 1). The lessons learned from these experiments and the associated adaptive restoration process can inform similar restoration and adaptive management projects.

Study Area and Management History

Zion NP was established in 1919 and is characterized by high mesas and deep canyons with steep cliffs that rise up to 1000 m above the river bottoms. Within the NFVR canyon, the river historically had a meandering channel and supported a riparian area with abundant shrubs, grasses, and trees (Wittwer 1927). Flood control revetments installed along a 7.2-km section of the NFVR in the 1920s and 1930s stabilized and raised the river banks, creating a straightened channel approximately 3.2 km long and confining the river to the western portion of the canyon. In the 80 years since revetment installation, the river channel has incised and floods rarely overtop the revetments to inundate the historic floodplain and terraces (McMahon et al. 2001). An unforeseen consequence of flood

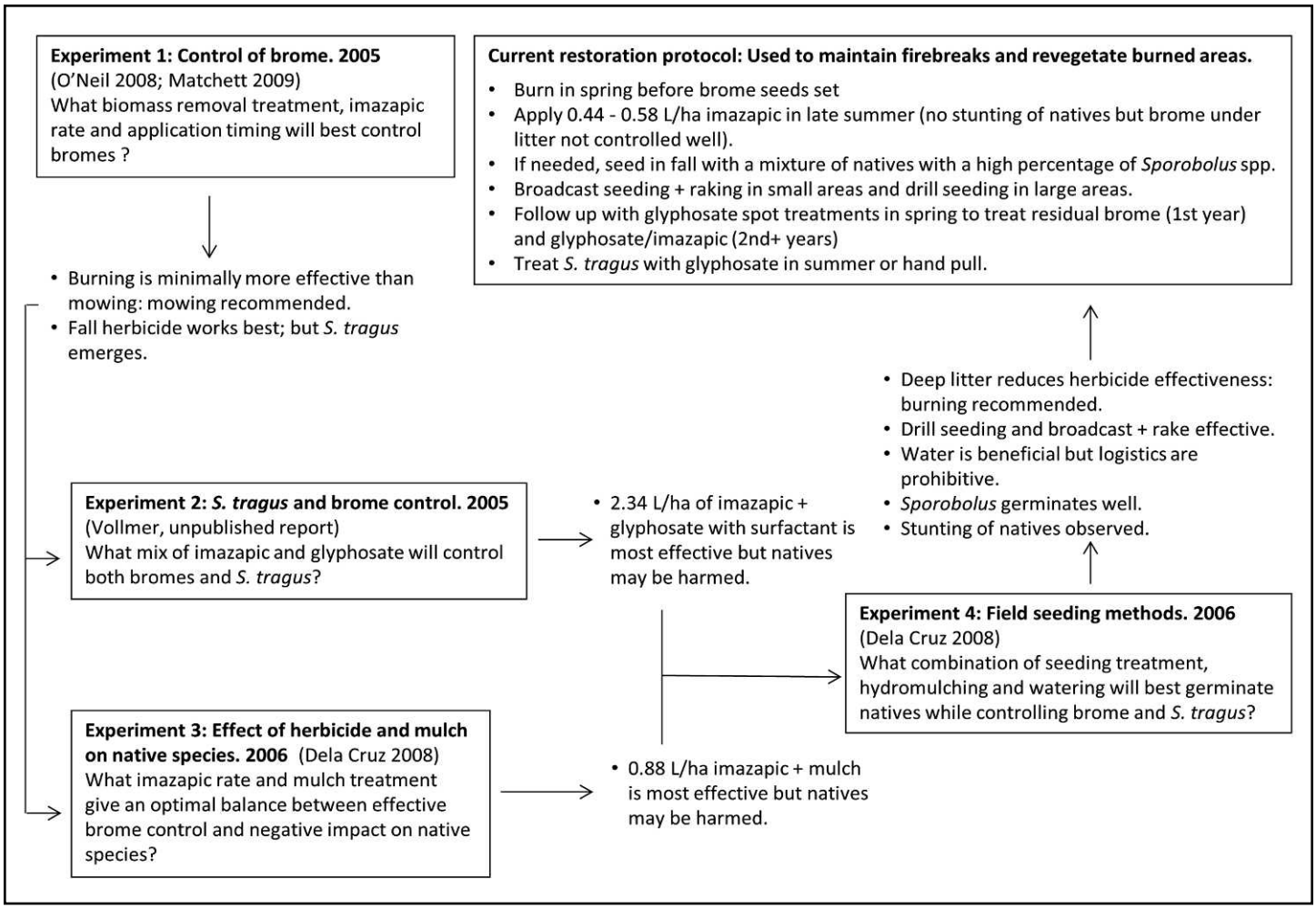


Figure 1. Data flow between preliminary experiments to inform an integrated riparian restoration project in Zion Canyon. Boxes show discrete studies with main questions. Arrows and corresponding text show the results that informed subsequent studies.

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curtailment is a substantial decrease in *Populus fremontii* S. Watson and *Salix* spp. recruitment in Zion Canyon (Braatne et al. 1996; McMahon et al. 2001; Steen-Adams 2002). Lack of flooding has also facilitated the colonization of exotic annual bromes on the historic floodplain and terrace surfaces, and these grasses are the dominant species in much of the canyon.

The Zion General Management Plan (National Park Service, 2001) recommended revetment removal along a 3.2-km river section where the ecosystem stressors are greatest. Revetment removal would potentially reinstate the hydrological connection between river and floodplain, improve vegetation and aquatic habitats for native species, and revive the *P. fremontii* and *Salix* spp. gallery forests of Zion Canyon. Increased flood frequency and intensity will likely remove bromes from the floodplain and lower terraces, but due to decades of downcutting, flooding is still not expected to reach the higher terraces (McMahon et al. 2001). Active restoration will be required to remove bromes and revegetate the terraces with native species. These activities would also address the public safety concerns associated with the threat of a potentially catastrophic brome-fueled fire within Zion Canyon, which receives the majority of ZNP's 3 million visitors each year.

While system-wide restoration needs exist, funding constraints led ZNP staff to decide to invest in multiple, modest experiments designed to identify solutions for controlling bromes and returning native vegetation to the riparian terraces. Preliminary planning exercises indicated that more information was needed on: (1) the best control measures to reduce brome cover and biomass, and (2) the most successful techniques for revegetating terraces with native plants. Here, we summarize four experiments aimed at addressing information needs and discuss associated management implications. Most experiments were undertaken as graduate student projects between 2004 and 2008. Complete treatment of the experiments is presented in the original graduate student theses or summarized in government reports (Dela Cruz 2008; O'Neil 2008; Matchett et al. 2009).

Experiment 1: Control of Bromes (O'Neil 2008; Matchett et al. 2009)

A high priority for ZNP management was to determine an effective strategy to remove brome biomass and prevent brome seed from germinating in the next season, in preparation for restoring the riparian terraces with native species. Through a Joint Fire Science Program research grant, Zion NP partnered with the United States Geological Survey, Lake Mead Exotic Plant Management Team, and the chemical company BASF to develop a study using the herbicide Plateau®, which contains imazapic, the most effective chemical for controlling brome (Davison and Smith 2007; Morris et al. 2009). Imazapic can act as a pre-emergent herbicide, preventing germination of annual species, as well as a post-emergent herbicide, killing germinated plants. Native perennial species, particularly warm-season grasses, are typically resistant to imazapic, although examples of stunting and mortality have been reported (Norcini et al. 2003; Davison and Smith 2007; Morris et al. 2009). Imazapic binds to organic matter, reducing its efficacy; reduction of nontarget organic matter increases effectiveness with lower rates of herbicide.

Methods: Experiment 1

Researchers and ZNP personnel designed an experiment with nine treatments that combined removal method (fall burning or mowing) with an herbicide application timing (fall = October; spring = February) and a seeding treatment (hand-seeding of native species or no seeding), in addition to a control treatment with no biomass removal, herbicide, or seeding. These treatments were replicated three times at each of four study sites for a total of 108 plots (Figure 1; Table 1). Burning was conducted using hand-held drip torches and mowing was done with a tractor-mounted flail mower or hand-held weed trimmers. The herbicide treatment consisted of a mixture of 0.88 L/ha of imazapic and 2.34 L/ha of methylated seed oil in the fall treatments, and 0.58 L/ha of imazapic in spring treatments. Higher concentrations were used in the fall due to the potential for leaching over the winter in the sandy soils. The seeding treatment consisted of a locally collected mixture of native seed, which was drilled or hand-seeded into plots at a rate of 3.42 to 5.70 kg/ha per species (O'Neil 2008; Table 2). Brome biomass and biomass of all other species were measured pre-treatment. These variables, as well as native species richness, cover, density, and diversity were measured one and two years post-treatment. Data were analyzed as a factorial randomized block design (Matchett et al. 2009). Model parameters, their standard errors, and statistical significance were calculated by maximum-likelihood estimation using functions contained within the Non-Linear Mixed Effects package (Pinheiro et al. 2008) for the R statistical software system (R Development Core Team 2008).

Results: Experiment 1

In the first year after the experiment, both burning and mowing reduced live brome biomass. Burning removed slightly more live biomass than mowing and far more litter than mowing. Fall herbicide application was markedly more effective in reducing brome biomass than spring application (Figure 2). Of the four removal/herbicide combinations, burning followed by fall herbicide application resulted in the greatest reduction of both brome biomass and density. Additionally, this was the only treatment combination that still had an effect on bromes in the second year of the study (Figure 2).

The effect of seeding on native species varied among treatments. One year after treatment, seeding increased the density of native perennials in both mowed and burned fall herbicide plots. Native species density was also high in burned spring herbicide plots regardless of whether or not they had been seeded. In treatments where native density increased, perennial grasses showed the largest increases. Two years after treatment, however, native plant density was not significantly different among any of the treatments (Figure 3). One surprise from this study was a dramatic increase in *Salsola tragus* L. across all treatments, with an average of 750 seedlings per plot, presumably due to decreased resource competition from bromes.

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Table 1. Hypotheses, experimental design summary, and data collection schedule for each of the four adaptive restoration experiments.

Experiment	Hypothesis/Objective	Plot Size	Treatment Schedule	Treatments	Replicates	Sites	Plots	Data Collection
1	• No a priori hypothesis as to effectiveness of mowing vs. burning or spring vs. fall herbicide application. • Seeding of natives after brome control would result in increased density of native species.	15 × 15 m	• September 2005 Burn and Mow· • October 2005 Herbicide • January 2006 Seeding· • February 2006 Herbicide	9	3	4	108	• May 2006 & April 2007 Brome biomass & density • Sept 2006 & 2007 Native density
2	• The highest rates of imazapic and glyphosate would control the most bromes and *S. tragus* .	3 × 9.1 m	• February 2006 Herbicide	15	3	1	45	• April 2006 Brome cover
3	• The highest imazapic rate would control the most bromes but would also stunt native species. • Mulch would increase water retention and germinate more species than no mulch.	4 L pot	• July 2006 Herbicide and seeding	8	15	N/A	120	• Sept 2006 Brome biomass & germination Native biomass & germination
4	• Drill seeding, hydromulching, and watering would be the most effective at germinating natives and controlling bromes and *S. tragus* .	3 × 6 m	• December 2006 All treatments seeded • March 2007 Herbicide • April 2007 Hydromulch • May - June 2007 Watering	14	5	2	136*	• Sept 2007 & 2008 Brome cover & germination Native cover & germination

* 4 plots were removed for analysis due to inaccurate herbicide application

Table 2. Native species and seeding rates used in Experiment 1.

Stratum	Scientific Name	Common Name	Family	Seeding Rate (PLS)
Grass	*Aristida purpurea*	Purple threeawn	Poaceae	3.36 kg/ha
Shrub	*Atriplex canescens*	Four-wing saltbush	Chenopodiaceae	3.36 kg/ha
Shrub	*Chrysothamnus nauseosus*	Rubber rabbitbrush	Asteraceae	4.48 kg/ha
Grass	*Elymus elymoides*	Squirreltail	Poaceae	5.60 kg/ha
Grass	*Sporobolus contractus* and *Sporobolus cryptandrus*	Spike dropseed combined with Sand dropseed	Poaceae	5.04 kg/ha

PLS = Pure live seed

Management Implications: Experiment 1

The results from Experiment 1 showed that burning was significantly more effective than mowing; however, ZNP staff felt that the small amount of additional brome control achieved by burning did not warrant the risk, expense, and management considerations involved in prescribed fire management, and, therefore, decided to use mowing to reduce brome biomass prior to future restoration projects (Figure 1). Fall application of imazapic was effective in controlling brome, but was ineffective on *S. tragus,* which emerged *en masse* after competition from brome was decreased. This result prompted further experiments with Journey® (imazapic + glyphosate), which was predicted to be effective on both species (Experiment 2; Figure 1).

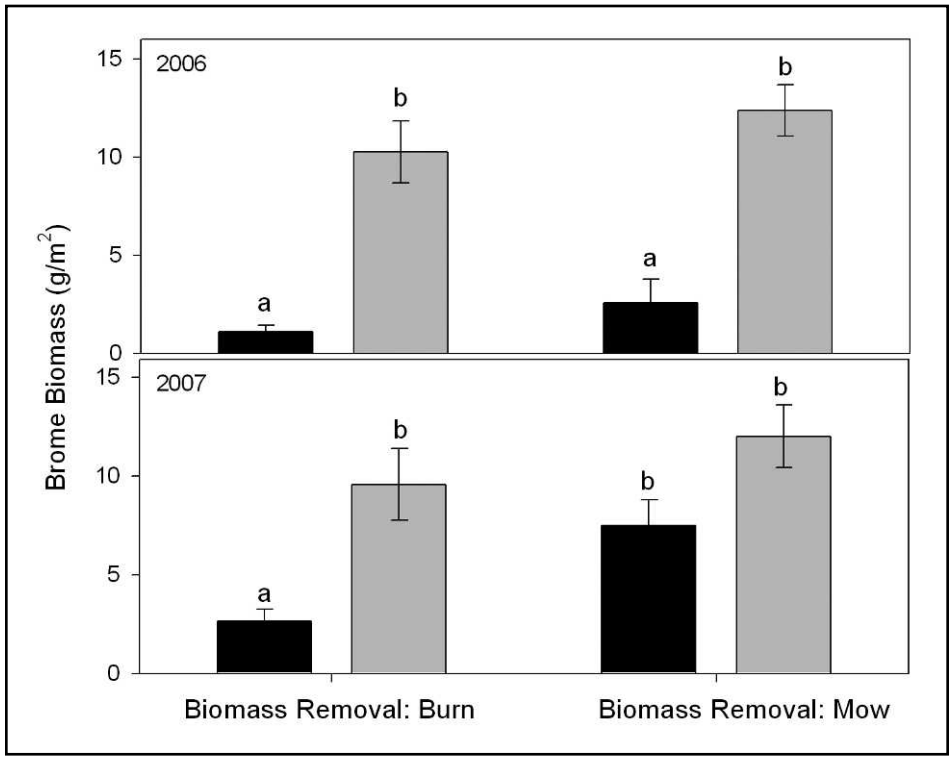


Figure 2. Biomass of brome regrowth after removal and herbicide treatments one growing season post restoration (top panel) and one year post restoration (bottom panel). Different letters denote significant differences among treatments ($P < 0.05$). Dark bars correspond to fall herbicide application, light bars are spring herbicide application.

High rates of imazapic application may also be affecting natural recruitment from the seed bank, as evidenced by the lower rates of recruitment when a higher concentration of imazapic was applied as a pre-emergent in the fall. Although a previous examination of terrace seed banks on the NFVR (Shorrock 2006) indicated that seeding was likely necessary for revegetation of the terraces, any seed that does germinate from the seed bank is an important resource for restoration. The potential negative effects of imazapic on native species germination prompted ZNP staff to investigate the effect of different herbicide application rates on germination and growth of native species (Experiment 3; Figure 1).

Experiment 2: Effectiveness of Herbicide Types and Application Rates (J. Vollmer, Weed Scientist, unpubl. data)

The results of Experiment 1 raised new questions regarding control of *S. tragus*, and the impacts of herbicide on native species. The success of the fall herbicide application versus spring suggested that imazapic worked much better for brome control as a pre-emergent herbicide or a foliar herbicide on new germinants rather than a foliar herbicide on mature plants. This result motivated ZNP staff to conduct further trials with Journey® (imazapic + glyphosate), which might be effective against both bromes and *S. tragus* (Experiment 2; Figure 1). Although brome was best controlled by imazapic applied in fall, *S.*

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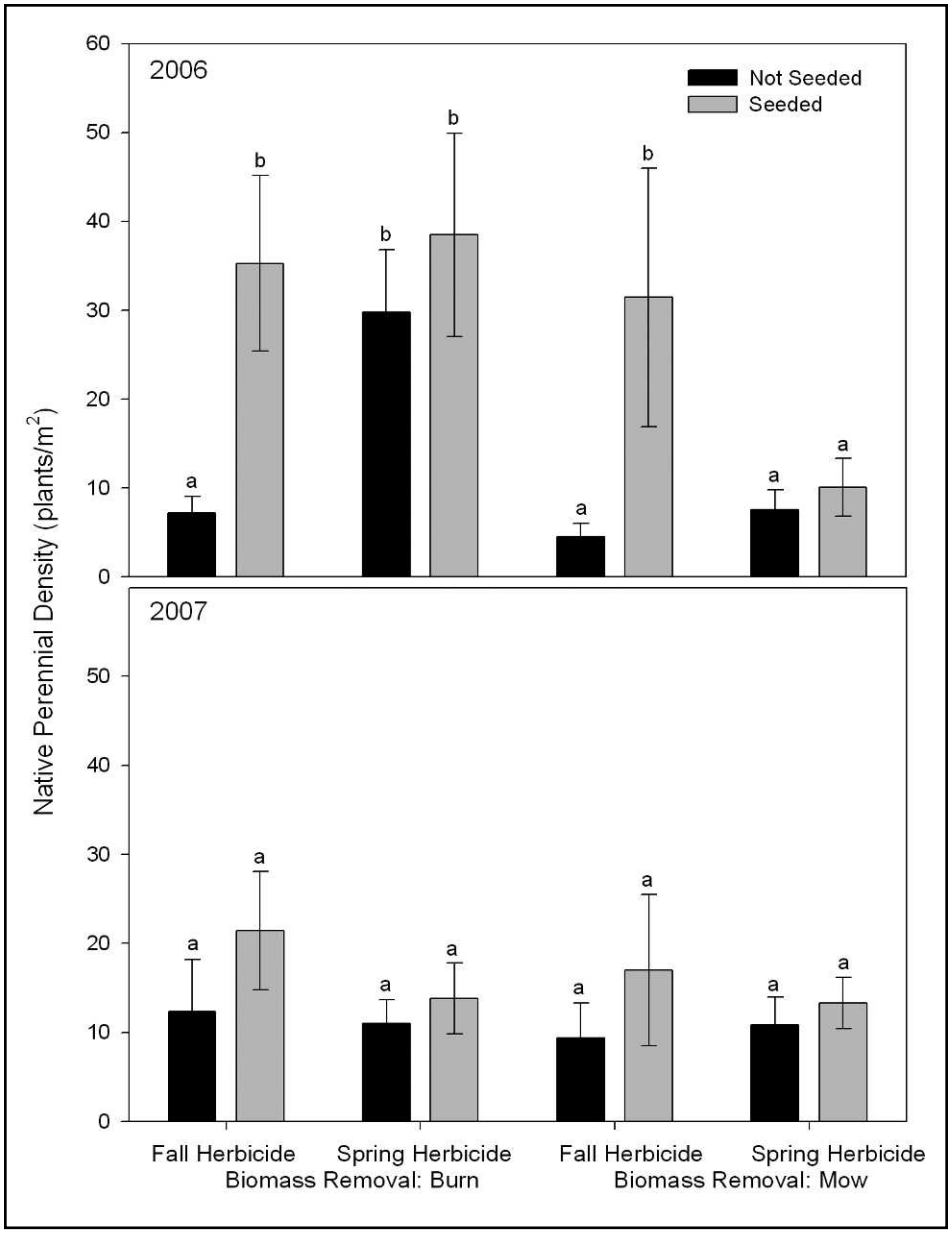


Figure 3. Native perennial seedling density after brome removal, herbicide and seeding treatments. Different letters denote significant differences among treatments ($P < 0.05$) one growing season after restoration (top panel) and one year after restoration (bottom panel).

tragus does not emerge until spring. Trials were planned for spring with the assumption that glyphosate would control both the *S. tragus* and the germinated bromes, while the imazapic would prevent germination of residual brome seed in the soil.

Methods: Experiment 2

The experiment consisted of two herbicide treatments (imazapic, imazapic + glyphosate), and two levels of surfactant (2.34 L/ha versus no surfactant). The imazapic trials included four herbicide application rates (0.44, 0.58, 0.73, 0.88 L/ha) and the imazapic + glyphosate trials included three application rates (1.16, 1.75, 2.34 L/ha). Each treatment combination and an untreated control were replicated three times for a total of 45 plots (Table 1). All treatments were applied in February 2006. Brome cover in each plot was visually estimated in April 2006 and compared with the untreated control plots.

Results: Experiment 2

Imazapic + glyphosate resulted in better brome control than imazapic alone, and surfactant enhanced the activity of both herbicides. Imazapic + glyphosate was also effective in controlling *S. tragus*. When using imazapic + glyphosate with a surfactant, the best control was achieved with 2.34 L/ha, the highest application rate tested. Time and funding constraints precluded collecting field data for this project. The difference among treatments was great enough to be obvious with simple observation.

Management Implications: Experiment 2

Based on the results of both Experiments 1 and 2, ZNP staff decided that late winter or early spring application of imazapic + glyphosate achieved an acceptable compromise between brome and *S. tragus* control. Glyphosate controlled *S. tragus* and existing brome because it targeted green vegetation, while imazapic acted as a pre-emergent for ungerminated brome seed in the soil (J. Vollmer, unpubl. data) (Figure 1).

Experiment 3: Effect of Herbicide and Mulch on Native Species (Dela Cruz 2008)

Few studies have investigated which imazapic rate would least affect germination of desirable native species, while still effectively controlling bromes (Kyser et al. 2007; Sheley et al. 2007; Morris et al. 2009). ZNP staff were also interested in the degree that brome mulch from dead or mowed plants might affect native and exotic species germination. Leaving mulch in place sometimes provides favorable site conditions for desired species and suppresses weeds (Kamara et al. 2000; Jodaugiene et al. 2006). In semi-arid climates, like that at ZNP, mulch may help conserve moisture and reduce soil compaction, water runoff, and soil erosion (Kay 1978; Munshower 1994). If beneficial, the addition of mulch to retard weed growth and conserve water would be a cost-effective, one-time event that would not require further maintenance.

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Methods: Experiment 3

Researchers and ZNP staff designed a mesocosm nursery experiment to test the interactive effects of mulching at two levels (mulch and no mulch) with imazapic treatments at four application rates (0, 0.29, 0.58, 0.88 L/ha) on six native species (Dela Cruz 2008; Table 3). Soil for this experiment was obtained from brome-dominated terraces at Zion and was assumed to contain brome seed. All pots were seeded with a mix of native species, treated with the appropriate concentration of imazapic, and then covered with brome mulch. This protocol simulated the hand broadcasting of native seed, applying herbicide, mowing the dead brome biomass, and leaving the brome biomass on site as mulch. The 0 L/ha herbicide + mulch treatment served as a control, because of the natural presence of mulch in the field. Imazapic alone rather than the imazapic + glyphosate mix was used because the herbicide was applied before seed germination. Glyphosate is only effective on extant vegetation. Each herbicide rate/mulch combination was replicated 15 times. Plants were grown for 10 weeks, after which the number of seedlings of each species was counted. Analyses were performed using a 2-way ANOVA, considering the interactive effects of herbicide rate and mulch on germination. Results with greater than two factors were analyzed using Tukey HSD multiple comparison tests to assess differences between treatments. All analyses were completed in JMP-IN 5.1 software (SAS Institute 2004).

Results: Experiment 3

The 0.58 L/ha-no mulch and 0.88 L/ha+mulch treatments were the most effective at controlling brome with the least harm to native species. Treatment with lower doses of herbicide failed to reduce brome germination (Figure 4). Use of 0.58 L/ha with mulch decreased the soil contact of the herbicide, which is necessary for effective control (BASF Corporation 2006), and resulted in less brome control. Use of 0.88 L/ha of imazapic with no mulch resulted in decreased native germination and stunting of plants that did germinate (Figure 4). Of the species examined, germination and growth of *Sporobolus* spp. and *Elymus elymoides* (Raf.) Swezey were the most dramatically affected at 0.88 L/ha. The addition of mulch partially ameliorated the negative effect of herbicide on *E. elymoides* but not on *Sporobolus* spp. *Sporobolus* spp. seedling density decreased by 95%–100% compared to the control (Figure 4). Mulching increased total native germination at all herbicide rates, but also had a positive effect on brome germination.

Management Implications: Experiment 3

While the highest herbicide application rate (0.88 L/ha) would be more expensive to apply, ZNP personnel recognized that this additional cost would be negligible compared to the costs, logistics, and management considerations involved in using prescribed fire to remove the mulch layer in preparation for an effective 0.58 L/ha herbicide application. Given variable conditions in the field, including soil texture, weed seed abundance, and the variable thickness in brome mulch cover that could decrease herbicide-to-soil contact, the higher application rate of 0.88 L/ha would increase the potential for brome control in more areas. Further, the higher application rate might provide longer-term control, as lower application rates generally last for only one season while higher rates can last for two to three seasons (Davison and Smith 2007; Elseroad and Rudd 2011). Ultimately, based on this experiment and input from ZNP management, the 0.88 L/ha + mulch treatment was chosen for further field trials (Figure 1).

In making this decision, ZNP staff acknowledged a tradeoff between brome control and significant stunting of at least one native species. The stunting effects of herbicide on *Sporobolus* spp. in the greenhouse mesocosm study corroborated information on the imazapic information label (BASF Corporation 2006), although the reduction was more drastic than expected.

Experiment 4: Field Seeding Methods (Dela Cruz 2008)

With the results of the experiments described above, ZNP eliminated a substantial amount of uncertainty concerning their ability to control bromes and restore native xeroriparian terraces along the NFVR. The remaining major uncertainties to be addressed before a large scale restoration

Table 3. Native species and seeding rates for Experiment 3. Conventional pure live seed rates could not be applied in small quantities so seeds were counted individually to ensure evenness among samples.

Stratum	Scientific name	Common name	Family	# seeds/pot
Shrub	*Atriplex canescens*	Four-winged saltbush	Chenopodiaceae	11
Shrub	*Chrysothamnus nauseosus*	Rubber rabbitbrush	Asteraceae	6
Forb	*Heterotheca villosa*	Hairy golden aster	Asteraceae	8
Grass	*Elymus elymoides*	Squirreltail	Poaceae	12
Grass	*Sporobolus contractus*	Spike dropseed	Poaceae	12
Grass	*Sporobolus cryptandrus*	Sand dropseed	Poaceae	12
			TOTAL	**61**

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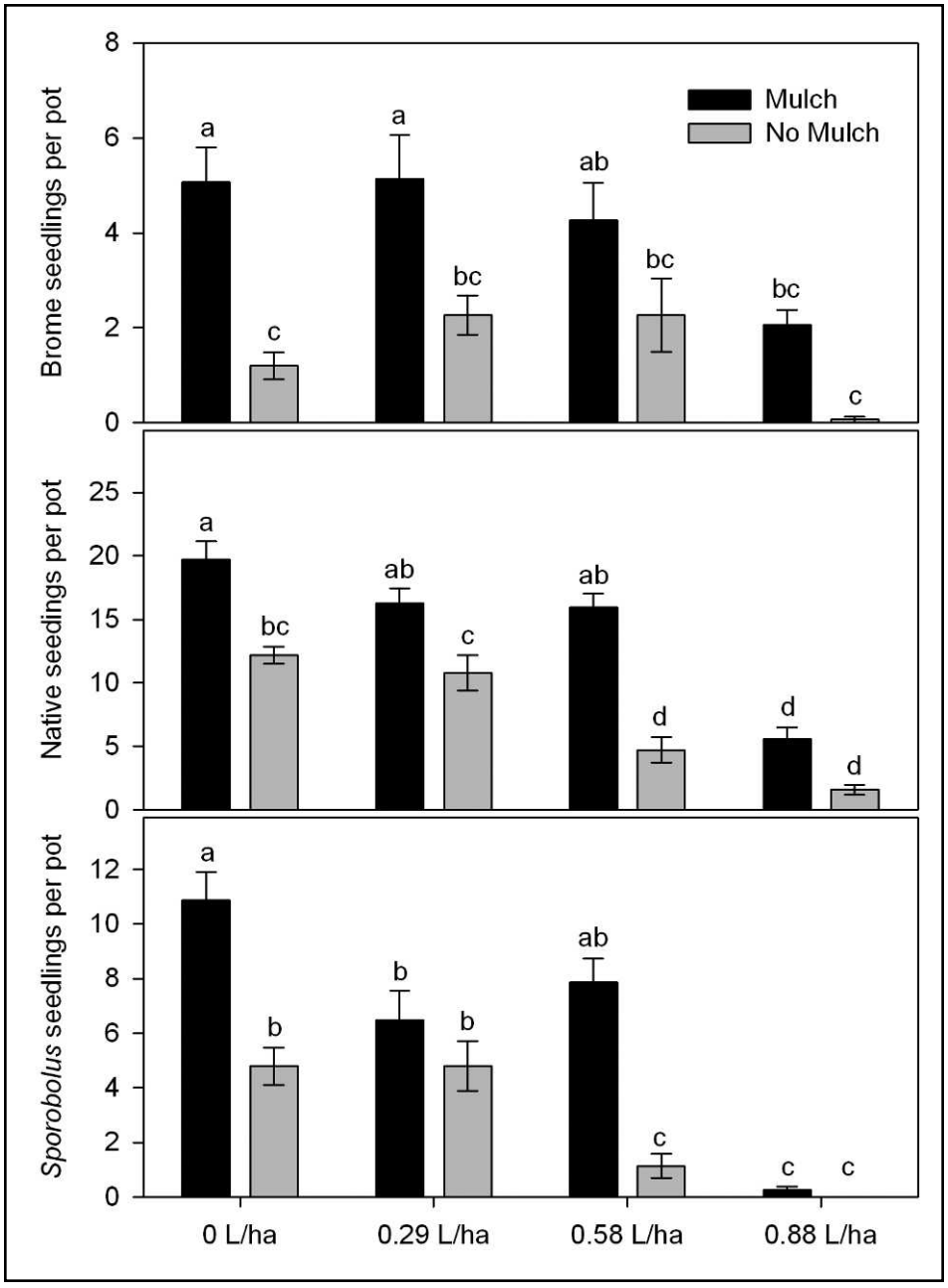


Figure 4. Seedling density in mesocosm pots after treatment with herbicide and mulch. Different letters denote significant differences among treatments ($P < 0.05$) for bromes (top panel), all native species seeded into mesocosms (middle panel) and *Sporobolus* spp. (bottom panel).

effort was attempted involved determining the most cost-effective methods to seed native species and promote germination. Zion NP personnel had traditionally hand-broadcast and raked in seed to create favorable soil to seed contact, but ZNP staff were interested in the efficacy of hand-broadcast seeding compared to drill seeding. Trampling during hand-broadcast seeding has minimal impacts to the area. Eliminating the raking step would minimize disturbance. Drill seeding would create furrows for seed, but the tractor and seeder would compact the soil. Zion NP staff also included a hydromulch treatment to determine if this treatment would increase native species germination, and a watering treatment to encourage native germination and determine the effects of an above average precipitation year on native germination and brome control.

Methods: Experiment 4

Zion NP personnel worked with researchers to design a small-scale field experiment that included herbicide (applied to all plots), seeding and raking (drill/hand, broadcast/hand, broadcast+raking), hydromulching (hydromulch/no hydromulch), and watering treatments (watered/unwatered). The final design included 12 treatments, plus a water-only control and an herbicide-only control, replicated five times across two sites. Standing brome biomass and litter were left at the sites to supply a mulch layer, as this increased native germination in Experiment 3.

Plots were seeded in late November 2006, using locally collected, native seed from species that grow abundantly in Zion Canyon (Dela Cruz 2008; Table 4). Eighty plots were broadcast-seeded by hand and half were lightly raked to facilitate soil-to-seed contact. An additional 40 plots were drill seeded with a small rangeland drill pulled by a tractor. Because all plots were located in an area that contained both bromes and *S. tragus*, an herbicide mix of imazapic + glyphosate + methylated seed oil at 0.88 + 1.16 + 2.34 L/ha was hand-applied by boom sprayer to all plots, based on the results of Experiment 2. Herbicide was applied in March when all native plants were dormant, in an attempt to target bromes and *S. tragus*, which had started their spring growth. One month after the herbicide application, hydromulch, consisting of biodegradable wood fiber, dye, and water (1680 kg/ha), was applied to a subset of plots. For three weeks in May and June, an additional 1.27 cm of water per week was irrigated onto half of the plots using a portable water pump that drew water from the NFVR. This treatment had to be abandoned before the end of the experiment as sediment from the NFVR frequently clogged sprinkler systems and repairs became too time-consuming.

Germination rates were measured in August 2007 and 2008 by counting the number of seedlings by species, per plot. A 3-way analysis of variance (ANOVA) with seeding method, watering, and mulch as factors and

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Table 4. Native species and seeding rates used for Experiment 4.

Stratum	Scientific Name	Common Name	Family	% Desired in Mix	Hand broadcast seeding rate (PLS)	Drill seeding rate (PLS)
Tree	*Robinia neomexicana*	New Mexican locust	Fabaceae	2.25	1.54 kg/ha	0.92 kg/ha
Tree	*Fraxinus anomala*	Singleleaf ash	Oleaceae	0.30	0.70 kg/ha	0.42 kg/ha
Tree	*Fraxinus velutina*	Velvet ash	Oleaceae	0.15	0.22 kg/ha	0.13 kg/ha
Tree	*Celtis reticulata*	Netleaf hackberry	Ulmaceae	0.30	0.97 kg/ha	0.58 kg/ha
Shrub	*Rhus aromatica* var. *trilobata*	Squawbush	Anacardiaceae	0.70	0.81 kg/ha	0.49 kg/ha
Shrub	*Chrysothamnus nauseosus*	Rubber rabbitbrush	Asteraceae	5.00	0.13 kg/ha	0.08 kg/ha
Shrub	*Atriplex canescens*	Four-wing saltbush	Chenopodiaceae	12.30	8.49 kg/ha	5.09 kg/ha
Forb	*Heterotheca villosa*	Hairy goldenaster	Asteraceae	10.00	0.40 kg/ha	0.24 kg/ha
Forb	*Penstemon palmeri*	Palmer's penstemon	Scrophulariaceae	10.00	0.81 kg/ha	0.48 kg/ha
Grass	*Elymus elymoides*	Squirreltail	Poaceae	20.00	1.37 kg/ha	0.83 kg/ha
Grass	*Sporobolus contractus*	Spike dropseed	Poaceae	19.25	0.14 kg/ha	0.08 kg/ha
Grass	*Sporobolus cryptandrus*	Sand dropseed	Poaceae	19.25	0.04 kg/ha	0.03 kg/ha
Grass	*Stipa hymenoides*	Indian ricegrass	Poaceae	0.50	0.05 kg/ha	0.03 kg/ha
			TOTAL	**100.00**	15.67 kg/ha	9.40 kg/ha

PLS = Pure live seed

blocked by site was used to evaluate treatment effects on native germination.

Results: Experiment 4

Herbicide application was effective and decreased the cover of exotic species to less than 1%; however, due to low levels of native recruitment, areas previously occupied by exotics were generally unvegetated in the first two years after treatment. During the second summer after treatment (2008), germinants of brome and *S. tragus* began to occupy the unvegetated areas. In 2008, brome and *S. tragus* accounted for 26% (3200+ seedlings) and 48% (12,000+ seedlings) of all germinants, respectively. After the number of germinants and cover of *S. tragus* were recorded in 2008, all *S. tragus* were pulled in all treatments to decrease competition with native species.

Native cover after herbicide treatment was similar to levels before treatment, indicating that the herbicide did not affect extant individuals, but very few new individuals recruited after treatment. Out of the 13 seeded species (Table 4), only four germinated in 2007 – *Sporobolus* spp. (two species), *Heterotheca villosa* (Pursh) Shinners, and *Robinia neomexicana* A. Gray. The majority of these germinants were *Sporobolus* spp., but most seedlings were stunted, as in Experiment 3. The cool season grass, *E. elymoides,* which germinated well in the greenhouse studies, did not germinate in the first year of the field study, likely because of insufficient winter rainfall in 2007. This species, along with four others, did germinate in 2008 after a more favorable winter rainfall regime, but *Sporobolus* spp. remained the most abundant species (Figure 5). Most of the native species germinated under a light cover of mulch as opposed to on bare ground or under deep mulch.

In 2007 and 2008, there was no difference in native germination for any species between seeding treatments (broadcast, broadcast+raking, drill seeder) or the hydromulch treatment. Water increased native germination in 2007, but this effect did not carry over to 2008 (Figure 6).

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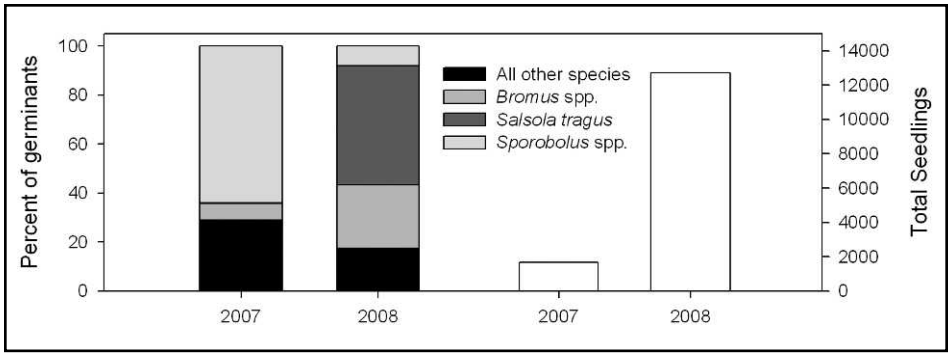


Figure 5. Seedling recruitment one growing season (2007) and one year (2008) after restoration treatments.

Results from this experiment highlighted an interesting interaction between bromes and *Datura wrightii* Regel, a native subshrub that is resistant to imazapic. Unexpectedly, the presence of *D. wrightii* favored bromes; in 2007, 39% of all bromes germinated under nurse plants, of which 97% were *D. wrightii*.

Management Implications: Experiment 4

Based on these results and those of previous studies, ZNP staff reconsidered using burning as an effective tool to eliminate the brome seedbank contained in the mulch, as it had proven difficult to treat some areas with deep mulch effectively with herbicide. While mulch is important for creating favorable microsite characteristics for native germination, the control of brome is paramount because of the strong competitive effects of brome on native species (Harris 1967; Rafferty and Young 2002; O'Neil 2008; Matchett et al. 2009). Spring burning would eliminate the thick litter layers beneath shrubs and trees that promote brome germination (Evans and Young 1970; Young and Evans 1975), but may also allow sufficient time for some litter to accumulate from native vegetation, which emerges later in the season. Low germination rates for trees and shrubs suggest that establishment of these species will probably require growing plants in tall pots to maximize root growth prior to transplanting (Bainbridge 1994). This study also demonstrated that *Sporobolus* spp. may be a good first year cover species, and managers may consider investing in seeding other warm-season perennial grasses that will continue to propagate as an alternative to using nonnative sterile annuals as a cover crop (Figure 1).

DISCUSSION

Adaptive Restoration at Zion National Park

The combination of increased fire threat and ecological degradation due to brome invasion put restoration of riparian areas and xeric terraces along the NFVR at the forefront of Zion NP management priorities. Prescribed fire is an effective method for removing standing brome biomass and accumulated litter. Additionally, fire may add nutrients from ash to the soil (Knoepp et al. 2005) to stimulate germination of seeded native species and those in the seed bank. The drawback to burning is that it requires a substantial amount of cost and planning and has to be timed to coincide with appropriate weather condi-

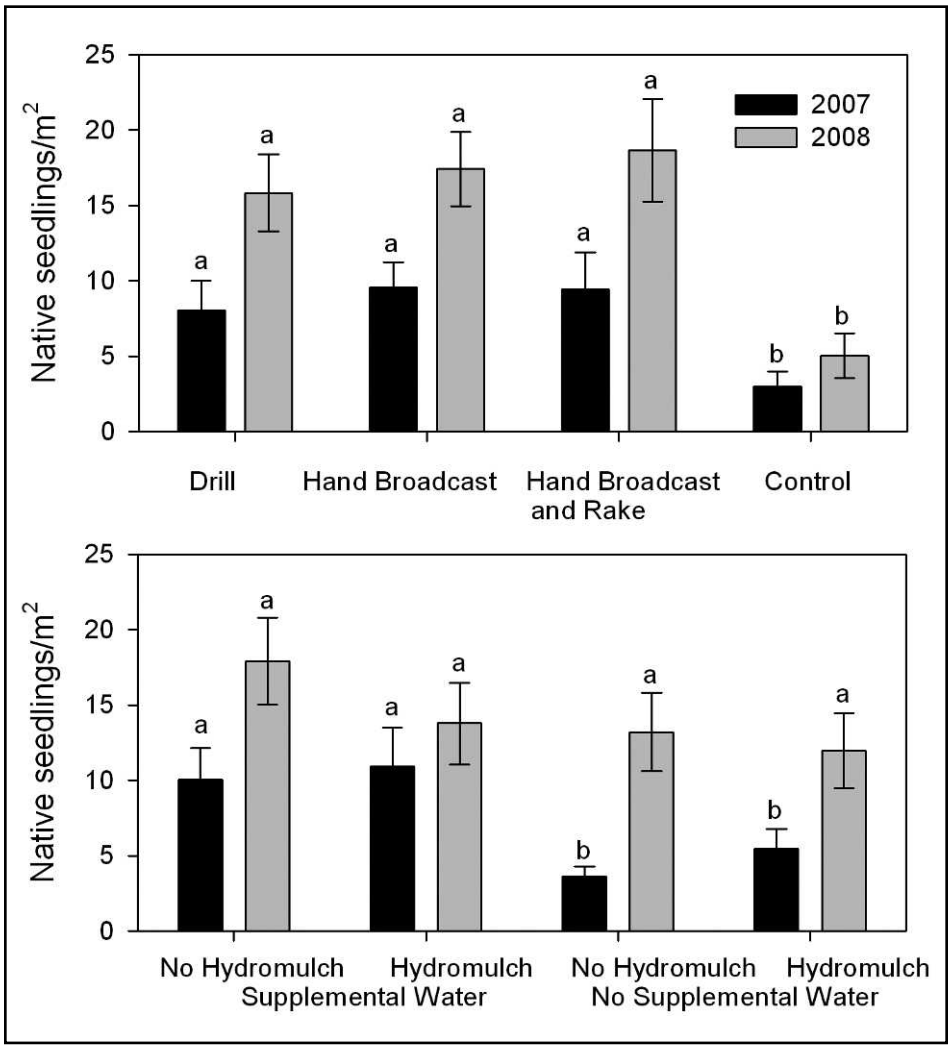


Figure 6. Effects of seeding treatment (top panel) and water and mulch treatments (bottom panel) on native seedling density one growing season and one year after restoration. Different letters denote significant differences among treatments within each year ($P < 0.05$).

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tions (Cleaves et al. 1999; Collins et al. 2010). Despite results from Experiment 1 showing that fall burning worked best to control bromes, ZNP was determined to test a variety of mowing and herbicide combinations to find an acceptable alternative to burning. Experiments 2 and 3 showed that herbicide application combined with mowing can control brome, but the high levels of herbicide required to penetrate the mulch left from mowing resulted in decreased recruitment and stunting of native species. Furthermore, experiment 4 showed that herbicide effectiveness is substantially decreased in areas with thick mulch. Despite these results, herbicide is still the method of choice at ZNP because of the coordination, planning, timing, and funding required for a prescribed fire. Due to the logistical difficulties associated with prescribed fire, ZNP staff is willing to accept the tradeoff of less efficient brome control that comes with relying on herbicide. When burning is possible, it is conducted in the spring just before the brome sets seed. Early spring burning also allows for later accumulation of litter from native species to create protected microsites for seed germination.

Herbicide application is critical for stopping brome germination and controlling other undesirable species such as *S. tragus*. Experiment 1 showed that imazapic is effective as a pre-emergent against bromes when applied before germination, but control of *S. tragus* and other broadleaf species requires glyphosate application directly to leaves later in the year. Experiments 2 and 3 showed that selection of herbicide concentration involves a tradeoff between brome control and stunting and decreased germination of desirable natives. Based on the results of these studies, ZNP managers have settled on using a 0.44–0.58 L/ha application of imazapic (depending on brome mulch depth) applied in late summer (Figure 1). This strategy does not harm natives, but is also not as effective against bromes in areas with litter accumulation, requiring a late winter/early spring glyphosate spot treatment on the resulting patches of germinated bromes. Glyphosate treatment of brome occurs too early to be effective against *S. tragus*, so these plants must be treated later in the year either with glyphosate or hand-pulling (often by volunteers). While this method is more labor intensive, this cost is offset by improved success of native species. In areas that do require seeding, a mixture of natives with a high percentage of *Sporobolus* spp. is sown in the fall, using broadcast seeding + raking (Figure 1).

The lessons learned from these experiments can be used to help determine priorities, examine tradeoffs, and design restoration plans in other brome-invaded areas of the American West. In the absence of controlled, replicated experiments, the consequences of one type of biomass removal method, both alone and in combination with other choices, such as herbicide application rates and timing, would be much less clear. When designing projects without this information, it would be much harder to anticipate the potential problems involved in a particular strategy and design a protocol with a high chance of success.

Institutional Considerations Associated with Adaptive Restoration

For an adaptive restoration approach to be successful, institutions in charge of large projects must be accepting of experimentation and the slow and steady pace of learning from these types of projects. Managers must also accept that some of the experiments may fail and realize that embracing the risk and uncertainty of this experimental approach is a way of building understanding (Lee 1993; Walters 1997; Zedler and Callaway 2003; Zedler 2006). When results indicate that particular treatments or actions are ineffective, managers must also be willing to alter plans and actions based on the information gained from experimentation. A key part of the success of this adaptive restoration process at ZNP has been the willingness of ZNP supervisors to develop and accept this type of iterative experiment and evaluation approach. The culture of collaboration between managers and scientists that these interactions have fostered at ZNP is instrumental to the success of adaptive restoration activities.

Another key aspect of the success of active restoration projects is the commitment of resources for implementation of restoration experiments and continued (possibly long-term) monitoring (Lee 1993). In the case of ZNP, the majority of this commitment did not come in a large block of funding, but through programs within the Department of the Interior that provide relatively small research grants. Zion NP also achieved cost savings by posing questions as a series of small studies suitable for graduate student theses. This approach allowed ZNP staff to access the expertise of several research universities for project design, monitoring, and data analysis, and conduct a considerable amount of research at a relatively low cost. A large group of dedicated volunteers who are actively involved in restoration projects has also been instrumental to research at ZNP. To date, volunteers at ZNP have donated hundreds of hours to collecting local seed and implementing the various treatments for the projects described above. This phased approach has eliminated a considerable amount of uncertainty from the design of the larger restoration project, and will likely reduce the costs and increase the efficiency of the ultimate project.

Admittedly, there are drawbacks to this adaptive restoration approach. Some projects may require immediate remediation efforts, making them unsuitable for the longer time-scale required with adaptive restoration (McAninch and Strayer 1989; Cabin 2007). Additionally, sites may be too small or variable to accommodate replicated experiments. Turnover in personnel, with potentially different values and agendas, can affect project trajectories, making long term planning difficult. Employing a series of graduate students from different institutions under different major professors can lead to quality control issues and lack of information flow, and can complicate the coordination of projects. In other cases, opportunities to collaborate with scientists and access peer-reviewed literature may be limited (Dettman and Mabry 2008).

A final drawback to the adaptive restoration approach is the often cited "implementation gap" between restoration science

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and restoration practice (Nature Editorial 2007). In adaptive management or adaptive restoration, the aim is to provide answers to very focused questions that pertain to a particular project (Schreiber et al. 2004; Taylor and Short 2009). However, broader scope projects that test general ecological principles are more likely to be funded by large national granting agencies and are viewed more favorably by editors of high impact journals (Cabin 2007; Taylor and Short 2009). In some instances, 'management science' projects can be designed to simultaneously test 'research science' questions (Zedler and Callaway 2003; Zedler 2005), but this seems to be the exception rather than the rule (Wagner et al. 2008).

The ultimate test of whether the adaptive restoration approach at ZNP has been successful will be the outcome of the full terrace restoration and revegetation project. In the meantime, ZNP staff have been able to put together a series of controlled, targeted experiments that will not only benefit their own efforts to control brome and restore native vegetation on NFVR terraces, but will also be of use to others dealing with brome invasions throughout the western United States (Mack 1981; D'Antonio and Vitousek 1992), and perhaps other semi-arid areas throughout the world (Bradford and Lauenroth 2006).

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Michelle P. Dela Cruz received her M.S. in Environmental Sciences and Policy from Northern Arizona University in 2008 where she researched riparian restoration techniques at Zion National Park. After working with the National Park Service for 10 years, she is currently an Environmental Protection Specialist for the Hazardous Fuels Reduction program at the Bureau of Indian Affairs Southwest Regional Office.

Vanessa B. Beauchamp is an Associate Professor in the Department of Biological Sciences at Towson University. Her research interests include plant community ecology with a focus on restoration, invasive species and mycorrhizal fungi.

Patrick B. Shafroth is a research ecologist with the U.S. Geological Survey, Fort Collins Science Center. Since 1991, Dr. Shafroth has conducted research on riparian ecosystems, primarily in arid and semi-arid regions of western U.S.A. He and colleagues have focused their work on understanding relationships between surface and ground-water hydrology, fluvial processes, and the dynamics of native and introduced riparian vegetation. This research has often been conducted in the applied context of riparian ecosystem restoration.

Cheryl Decker is currently the Vegetation Program Manager for the National Park Service's Southeast Utah Group (Canyonlands, Arches, Natural Bridges, and Hovenweep) based in Moab, Utah. She arrived at Zion as the Native Plant Nursery Manager and Restoration Specialist in 2001 and from 2005–2011, she was the Vegetation Program Manager at Zion National Park. Her background is in Plant Propagation, Weed Management, Restoration, and Planning and Public Policy.

Aviva O'Neil received a Masters in Agriculture from Iowa State University. She currently lives and works in Zion National Park.

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