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Direct effects of soil amendments on field emergence and growth of the invasive annual grass *Bromus tectorum* L. and the native perennial grass *Hilaria jamesii* (Torr.) Benth

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Abstract

Bromus tectorum L. is a non-native, annual grass that has invaded western North America. In SE Utah, *B. tectorum* generally occurs in grasslands dominated by the native perennial grass, *Hilaria jamesii* (Torr.) Benth. and rarely where the natives *Stipa hymenoides* Roem. and Schult. and *S. comata* Trin. & Rupr. are dominant. This patchy invasion is likely due to differences in soil chemistry. Previous laboratory experiments investigated using soil amendments that would allow *B. tectorum* to germinate but would reduce *B. tectorum* emergence without affecting *H. jamesii*. For this study we selected the most successful treatments ($CaCl_2$, $MgCl_2$, NaCl and zeolite) from a previous laboratory study and applied them in the field in two different years at *B. tectorum*-dominated field sites. All amendments except the lowest level of $CaCl_2$ and zeolite negatively affected *B. tectorum* emergence and/or biomass. No amendments negatively affected the biomass of *H. jamesii* but NaCl reduced emergence. Amendment effectiveness depended on year of application and the length of time since application. The medium concentration of zeolite had the strongest negative effect on *B. tectorum* with little effect on *H. jamesii*. We conducted a laboratory experiment to determine why zeolite was effective and found it released large amounts of Na^+, adsorbed Ca^{2+}, and increased Zn^{2+}, Fe^{2+}, Mn^{2+}, Cu^{2+}, exchangeable Mg^{2+}, exchangeable K, and NH_4^+ in the soil. Our results suggest several possible amendments to control *B. tectorum*. However, variability in effectiveness due to abiotic factors such as precipitation and soil type must be accounted for when establishing management plans.

Introduction

Resource competition theory predicts that some species are better competitors than others for certain resources, and therefore, resources can determine plant community structure (Grover, 1997; Tilman, 1982; Tilman, 1990). Thus, altering resource availability using soil amendments can alter competition between plants (Bilbrough and Caldwell, 1997; DiTommaso and Aarssen, 1989; Güsewell et al., 2003; Kay and Evans, 1965; Lowe et al., 2003; Tilman et al., 1999; Yoder and Caldwell, 2002) and may be even considered a form of biological control for weeds (Tilman et al., 1999). Resource biological control is achieved by finding a resource that is limiting for the weedy species but not the desired species. For example, Tilman et al. (1999) found that *Taraxacum officinale* G.H. Weber ex. Wiggers was

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limited by potassium (K); therefore, fertilizers with low K reduced *T. officinale* density by reducing its competitive ability relative to *Festuca rubra* L. Carbon (C) amendments (such as sugar, sawdust and wood chips) can reduce soil nitrogen (N) and have been widely used to control annual weeds (McLendon and Redente, 1991; Morghan and Seastedt, 1999). Although such C amendments can be effective, sugar is expensive and sawdust and wood chips require significant labor and create large disturbances. Therefore, finding other methods to alter soil resources may be a better way to control invasive plants.

Bromus tectorum L. (cheatgrass) is an annual, invasive grass that is native to Europe, northern Africa, and southwest Asia. However, it is now abundant in several countries around the world and has invaded millions of acres in western North America since the late 1800's (Klemmedson and Smith, 1964; Mack, 1981; Novak and Mack, 1993). *Bromus tectorum* invasion can have profound consequences for ecosystems by altering nutrient (Evans et al., 2001) and fire cycles (Grace et al., 2001; Peters and Bunting, 1992; Whisenant, 1989). In addition, *B. tectorum* can also alter soil food webs (Belnap and Phillips, 2001) and lead to the endangerment or extirpation of other species (Rosentreter, 1994).

The negative impacts of *B. tectorum* invasions have prompted researchers and land managers to search for effective control methods. Grazing has been used to control *B. tectorum*; however, it does not appear to be effective (Vallentine and Stevens, 1994). Herbicides have also been widely studied but are expensive and detrimental to human and environmental health. Although glyphosate herbicides can have negative effects on *B. tectorum* seedlings, little is know about effects on the native community (Beck et al., 1995). The rhizobacterium, *Pseudomonas fluorescens*, and several species of crown and root rot fungi have been investigated as biological controls; however, their use may be limited and their effectiveness is uncertain (Grey et al., 1995; Tranel et al., 1993a, b). Despite the use of all these control methods, *B. tectorum* is still abundant throughout North America.

In Canyonlands National Park, Belnap and Phillips (2001) documented that *B. tectorum* generally occurs in areas dominated by the native, perennial grass *Hilaria jamesii* (Torr.) Benth. and only rarely occurs in areas dominated by the natives *Stipa hymenoides* Roem. and Schult. and *S. comata* Trin. & Rupr. Subsequent studies found that the invasion pattern was due to differences in available phosphorus (P) and K in the soils (Belnap et al., in review; Newingham et al., in review). For example, *B. tectorum* success has been found to be positively associated with soil P availability (e.g., P/calcium carbonate ($CaCO_3$), P/manganese (Mn^{2+}); Belnap et al., in review; Miller, 2000). $CaCO_3$ and reactive oxides, such Mn^{2+}, zinc (Zn^{2+}), and iron (Fe^{2+}) oxides, can bind with P making it unavailable to plants (Lajtha and Schlesinger, 1988; Miller, 2000). Carreira and Lajtha (1997) found that adding $CaCl_2$ to a calcareous entisol reduced available P, probably by Ca^{2+} inducing the precipitation of $CaCO_3$. Thus, using soil amendments containing Ca^{2+} to limit P availability may reduce *B. tectorum*.

In contrast to P, much less work has been done with K as a limiting nutrient in dryland soils. Plant species differ in their K uptake, which is positively and highly correlated with their root cation exchange capacity (CEC; $R2 = 0.77$ as reported in Crooke and Knight (1962) and Gray et al. (1953)). Root CECs of annual grasses are generally 2–5× higher than associated native grass root CECs (Belnap et al., unpublished data). Annual grasses can also have much higher tissue K concentrations than adjacent native plants (R. Blank, personal communication), which may indicate that annual grasses have a higher requirement for K than the native grasses (Tilman, 1982).

Studies have found that *B. tectorum* growth is positively associated with K availability (Belnap et al., in review; Howell, 1998; Morrison, 1999). Both magnesium (Mg^{2+}) and calcium (Ca^{2+}) can inhibit the uptake of K by plants (Brady and Weil, 1996; Haynes and Goh, 1978; Thompson and Troeh, 1978), and thus K/Mg^{2+} and K/Ca^{2+} can determine K availability and thus *B. tectorum* success. Increased sodium chloride (NaCl) has been found to reduce K in olive trees (Loupassaki et al., 2002), and Belnap et al. (2003) found *B. tectorum* to be salt-sensitive in laboratory studies regardless of the type of salt.

The positive correlation between P and K availability and *B. tectorum* suggests that P and K limit these plant communities in Canyonlands

National Park; therefore, using soil amendments such as Ca^{2+}, Mg^{2+} and Na^{+} compounds to reduce K and/or P may prove to be an effective method of control for *B. tectorum*. Belnap et al. (2003) investigated several soil amendments to reduce the emergence of *B. tectorum* in the laboratory. They found zeolite, a high-cation exchange capacity (220 $cmol_c\,kg^{-1}$), crystalline, hydrated aluminosilicate of volcanic origin (Ming and Mumpton 1989), to be one of the most effective amendments at reducing *B. tectorum* emergence. Zeolite may be pre-charged with certain ions to exchange them for other ions in the soil (Williams and Nelson, 1997). Belnap et al. (2003) charged zeolite with Na^{+} by saturating it in NaCl (see below), resulting in Na^{+} being released into the soil in exchange for other cations. The negative effects of zeolite with NaCl suggest that *B. tectorum* may have a low tolerance for Na^{+} toxicity. Other compounds including high salt applications, K-reducing additions, and P-reducing additions showed promise at controlling *B. tectorum*; however, these amendments were only applied in a laboratory setting.

In this study, we conducted field soil amendment experiments to test the hypothesis that altering soil chemistry could reduce *B. tectorum* success. For these experiments, we manipulated P and K availability in the field to reduce the emergence and biomass of *B. tectorum*. We selected four amendments from Belnap et al. (2003) that suppressed *B. tectorum* emergence without affecting *H. jamesii*: $CaCl_2$, $MgCl_2$, NaCl and zeolite. We applied the amendments at various concentrations and seeded *B. tectorum* or *H. jamesii* at two field sites dominated by *B. tectorum* to test their feasibility and efficacy in the field.

Materials and methods

Site description

Field experiments were conducted in the Needles District of Canyonlands National Park, Utah (N 38°15′, W 109°79′, 1525 m elevation, average annual precipitation 214 mm). We applied field soil amendments at two sites previously dominated by *H. jamesii* but have been dominated by *B. tectorum* for the past 50 years. Soils were part of the Begay series and are classified as fine sandy loam. Precipitation events were recorded from September 1, 2001 until June 1, 2003. Soil water content at 10 cm was also recorded with a Campbell data logger.

We collected soils at 0–10 cm depth from the two sites (30 subsamples) and analyzed them for texture and chemistry before amendments were applied. Available P (Olsen et al., 1954) and available K (Schoenau and Karamonos, 1993) were extracted with $NaHCO_3$. Zn^{2+}, Fe^{2+}, Mn^{2+}, and copper (Cu^{2+}) were extracted with diethyltriaminepentaacetic acid (Lindsay and Norwell, 1978). All exchangeable cations (Ca^{2+}, Mg^{2+}, K, Na^{+}) were extracted with ammonium acetate ($NH_4C_2H_3O_2$; Thomas, 1982). Acid neutralizing potential (the combination of $CaCO_3$ and Zn^{2+}, Mn^{2+}, Fe^{2+}, and Mg^{2+} oxides) was measured by hydrochloric acid (HCl) neutralization (Allison and Moodie, 1965) and thus includes any soil constituents that neutralize acid. Texture was determined by the hydrometer method, and total N was determined by Kjeldahl analysis (Bremner, 1996). Nitrate (NO^{3-}) and ammonium (NH^{4+}) soil analysis was conducted using a modified 2 *M* KCl extraction (Bremner and Keeney 1966) and colorimetrically analyzed by flow injection on a Lachat QuikChem 8000. Cation exchange capacity was analyzed by sodium saturation followed by NH^{4+} displacement (Rhoades, 1982).

Treatments

At each site we buried PVC pipes vertically that were 15 × 20 cm in diameter to restrain horizontal movement of the applied amendments in the soil. Round hardware cloth cages (15 × 46 cm, ¼″ mesh) were placed over all plots to prevent rodent herbivory. All amendment concentrations (except zeolite, a solid) were added at equivalent osmolar rates using the procedure described by Cannon et al. (1995) as a guide for additive levels (Table 1). Clinoptilolite (a form of zeolite obtained from GSA Resources, Inc., Tucson, AZ) was charged with Na^{+} by equilibration with 2 *M* NaCl for 5.5 days, during which the solution was shaken and replaced every 24 h. We then drained the excess NaCl and dried the zeolite in a drying oven at 60 °C. We defined

Table 1. Amendment amounts added per gram of soil for each concentration of amendment

Concentration	Amendment	Amount added (mg)
4×	$CaCl_2$	2.4
5×	$CaCl_2$	3.0
3×	$MgCl_2$	3.3
4×	$MgCl_2$	4.4
4×	$NaCl_2$	4.0
0.5×	Zeolite	50.0
1×	Zeolite	100.0
2×	Zeolite	200.0

All amendments were applied in 100 ml deionized water.

1 × zeolite concentration for this study as that which effectively suppressed *B. tectorum* in the laboratory (Belnap et al., 2003) and used that and other derivative amounts (0.5×, 2×) for this experiment.

Experiment 1 commenced in September 2001 and was harvested in May 2002. We applied deionized water as a control or one of the following six amendments: 4× $CaCl_2$, 5× $CaCl_2$, 3× $MgCl_2$, 4× $MgCl_2$, 4× NaCl, and 1× zeolite (7 treatments × 5 replicates × 2 sites = 70 plots). All amendments (except zeolite) were applied in 100 ml of deionized water and 100 ml of deionized water was applied to controls (Table 1). Zeolite was applied in dry form, mixed into the top 1 cm of soil, and 100 ml of deionized water was added to the plot. After amendments were applied, 10 *B. tectorum* seeds were planted using a grid to track emerging seedlings. Seedling emergence was monitored monthly, and after maximum emergence, seedlings were thinned to five well-established individuals. Germination rates were unknown, as we did not want to disturb soil by digging for ungerminated seeds. Aboveground biomass was harvested just before seed set in May, dried at 60 °C for 48 h, and weighed.

To assess the residual effects of these amendments, we reseeded the same plots in September 2002 but did not reapply the amendments. Emergence was monitored monthly and seedlings were thinned to five individuals. In May 2003 plants were harvested as stated above.

Experiment 2 commenced in September 2002 and plants were harvested in May 2003. For this experiment, we applied water as a control or one of the following six amendments: 5× $CaCl_2$, 4× $MgCl_2$, 4× NaCl, 0.5× zeolite, 1× zeolite, and 2× zeolite (7 treatments × 5 replicates × 2 sites = 70 plots). These plots were planted with 10 *B. tectorum* seeds using a grid. In addition, we applied water as a control and 5× $CaCl_2$, 4× $MgCl_2$, 4× NaCl, and 1× zeolite to another 50 plots and planted 10 *H. jamesii* seeds. Plants were monitored, thinned, and harvested as in Experiment 1.

NaCl and zeolite were the most effective amendments in Experiments 1 and 2. Thus, to better understand the effects of our additions on soil chemistry, post-amendment soils for the NaCl treatments in Experiment 1 were analyzed for all exchangeable cations as described above after the second year of the experiment. We were not able to analyze zeolite-treated soils as it was impossible to separate the zeolite from soil and thus would have only given us amounts in the zeolite/soil mixture. Instead, we conducted a laboratory experiment to determine the effect of zeolite on nutrients in the soil. We placed 30 g of zeolite in 7 × 13 mm mesh polypropylene bags (Spectrum Laboratories) and placed the bags in 1-quart mason jars with 320 g soil and 400 ml deionized water ($n = 6$). Jars were shaken every 2 h during the daytime for 2 weeks to assure soil stayed in solution. Bags were removed from the jars and rinsed with deionized water. The zeolite and soil were allowed to air dry. In another six jars, we placed 320 g soil and 400 ml deionized water with no zeolite. We analyzed the soil for available P, available K, NH_4^+, NO_3^-, micronutrients (Zn^{2+}, Fe^{2+}, Mn^{2+}, Cu^{2+}), and exchangeable ions (Ca^{2+}, Mg^{2+}, K, Na^+) in both the soil + water + zeolite and soil + water treatments. Soil + water values were subtracted from soil + water + zeolite values to determine how zeolite affected soil nutrients.

Statistical analyses

Biomass data are reported as an average biomass per individual per plot. Total plot biomass showed similar patterns and thus is not presented. Initially, emergence and biomass data were analyzed with a two-way ANOVA with site and amendment as fixed factors; however, there were no site differences in any analyses and the

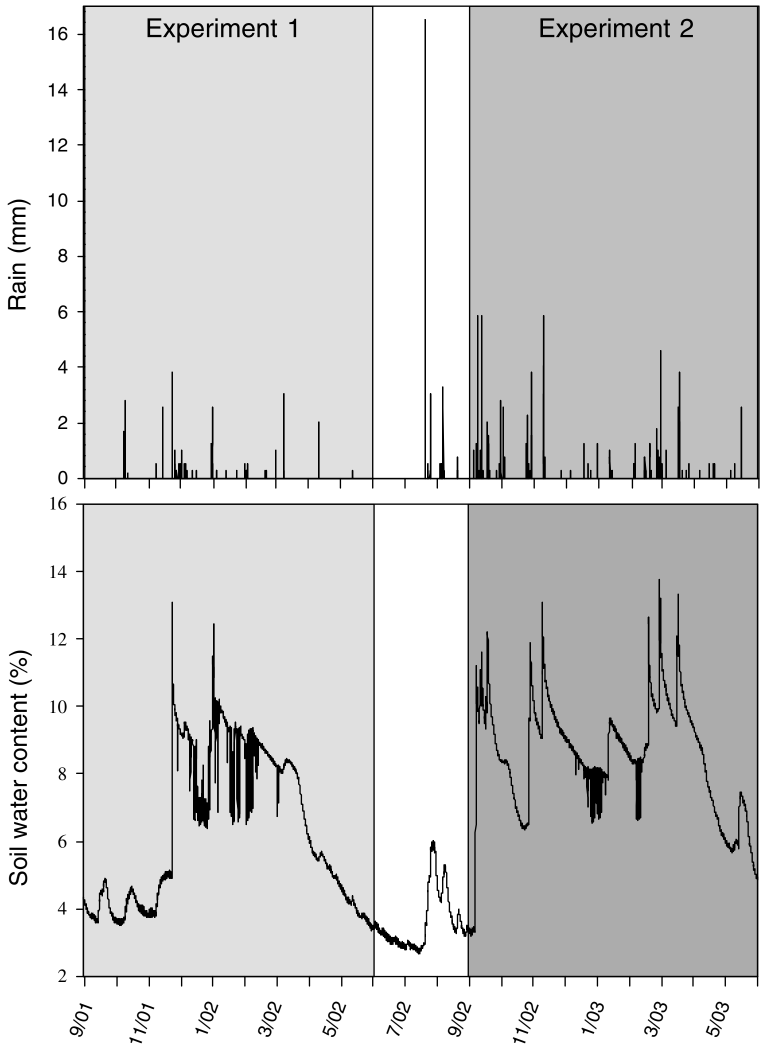

Figure 1. (a) Rain events at Squaw Flat during the 2001–2002 and 2002–2003 experiments. (b) Soil moisture content at 10 cm depth in Canyonlands National Park during 2001–2003.

two sites were combined. Since we are only interested in whether certain amendments were significantly different from the controls and not from each other, we then compared individual amendments to the control using independent samples *t*-tests. Exchangeable cation data were compared between control and NaCl-treated soils using independent sample *t*-tests. Soil chemistry data from the zeolite experiment were also analyzed using independent sample *t*-tests. Analyses were run on SPSS version 12. Differences were considered statistically significant at $P < 0.05$ unless otherwise noted in the text.

Results

Abiotic conditions

The 40-year average precipitation for September through May in the Needles District of Canyonlands National Park, Utah, is 156 mm; however, the total precipitation during experiment 1 (2001–2002) for September through May was only 55 mm. During the 3 months (June 2002–August 2002) that lapsed between experiments, Needles received 34 mm of precipitation. Total precipitation was 169 mm during Experiment 2 (September–May,

Table 2. Soil chemistry at the study site in Squaw Flat, Needles District, Canyonlands National Park

Available P	9
Total N	179
Available K	162
Zn^{2+}	0.3
Fe^{2+}	2.2
Mn^{2+}	3.6
Cu^{2+}	0.5
Exchangeable Na^{+}	58
Exchangeable Ca^{2+}	3179
Exchangeable Mg^{2+}	148
Exchangeable K	266
P/Mg^{2+} (ex)	1.8
K (avail) Mg^{2+} (ex)	1.1
Acid neutralizing potential (%)	5
Sand (%)	73
Clay (%)	13
Silt (%)	15
Cation exchange capacity (EC meq/100 g)	5

Units are μg nutrient/g soil unless otherwise indicated.

2002–2003) and thus was three times greater than that received during Experiment 1 (Figure 1). Soil water content from June 2001 through May 2003 is shown in Figure 1. In the fall when *B. tectorum* germinates, soil water content was higher in Experiment 2 than in Experiment 1. Additionally, soil water content was higher at the end of the spring growing season in Experiment 2. Soil chemistry characteristics of the experimental site are described in Table 2.

Emergence and biomass in Experiment 1

Adding certain soil amendments significantly reduced *B. tectorum* emergence in Experiment 1 (Figure 2a). Whereas 4× $CaCl_2$, 3× $MgCl_2$, and 4× NaCl had no significant effect on *B. tectorum* emergence compared to controls, 5× $CaCl_2$, 4× $MgCl_2$, and 1× zeolite reduced *B. tectorum* emergence ($P = 0.07$, $P = 0.03$, $P < 0.001$, respectively). When *B. tectorum* was reseeded into plots without amendments reapplied, only the 4× $MgCl_2$ amendment had a significant effect on *B. tectorum* emergence (Figure 2b, $P = 0.05$); however, this effect was stimulatory. The amendment 3× $MgCl_2$ also showed a trend towards increasing emergence ($P = 0.10$).

A few soil amendments applied in Experiment 1 also had a negative effect on *B. tectorum* shoot biomass in 2001 (Figure 2c). Similar to the emergence results, 4× $CaCl_2$, 3× $MgCl_2$, 4× $MgCl_2$, and 4× NaCl had no effect on biomass, whereas 5× $CaCl_2$ and 1 × zeolite had negative effects on biomass compared to controls ($P = 0.03$, $P = 0.003$, respectively). In 2002 when *B. tectorum* was reseeded into plots without amendments reapplied, only 1× zeolite negatively affected *B. tectorum* biomass (Figure 2d, $P = 0.05$).

Emergence and biomass in Experiment 2

In Experiment 2 some soil amendments also had a significant effect on *B. tectorum* emergence (Figure 3a). Adding 5× $CaCl_2$, 4× $MgCl_2$, 0.5× zeolite, and 1× zeolite had no effect on emergence compared to controls. In contrast, 4× NaCl and 2× zeolite had negative effects on emergence ($P = 0.03$, $P = 0.006$, respectively). Soil amendments in Experiment 2 also had a significant effect on *H. jamesii* emergence (Figure 3b), as the NaCl amendment reduced emergence ($P = 0.06$).

Applying soil amendments had little effect on *B. tectorum* biomass in Experiment 2 (Figure 3c), as only 0.5× zeolite tended to decrease *B. tectorum* biomass ($P = 0.08$). No soil amendments had strong effects on *H. jamesii* biomass (Figure 3d), although 1× zeolite showed a tendency to increase *H. jamesii* biomass ($P = 0.10$).

Changes in soil chemistry after 1 year and effects of zeolite

Exchangeable soil cations in the control and NaCl-treated soils after the second year of Experiment 1 are listed in Table 3. The NaCl treatment solution had a concentration of 730 μg Na^{+} g soil, which was added to the background 58 μg in the soil. We presumed that this addition was, at least initially, additive, resulting in a total of 788 μg Na^{+} g soil; however, Na^{+} levels were not determined immediately after application. At harvest 2 years later, there was 247 μg Na^{+} g soil left in the NaCl-treated plots, indicating there had been a 69% decrease 2 years after application of NaCl, presumably due to leaching in the soil and/or plant uptake. After 2 years there were

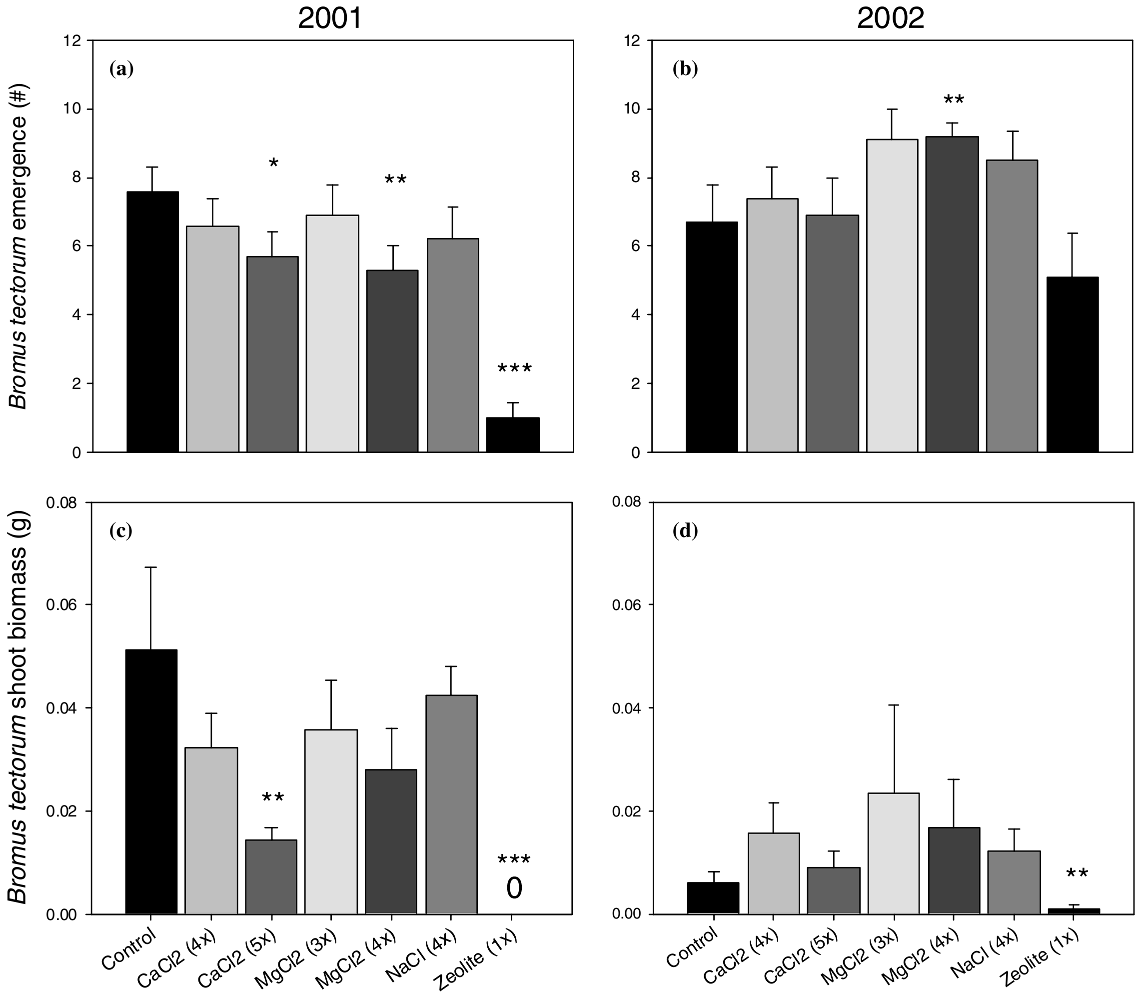

Figure 2. Effects of soil amendments on *Bromus tectorum* for Experiment 1. (a) Emergence (out of 10) in 2001 immediately after amendments were applied. (b) Emergence the following growing season (2002) without additional amendments applied. (c) Shoot biomass in 2001. (d) Shoot biomass in 2002. Numbers in parentheses signify amendment concentrations. Error bars represent ±1 standard error. * = $P \leq 0.10$; ** = $P \leq 0.05$; *** = $P \leq 0.001$.

decreases in exchangeable Ca^{2+}, Mg^{2+} and K ($P = 0.003$, $P = 0.001$, $P = 0.03$, respectively) in the NaCl treated soils compared to the control.

In the laboratory when we tested how zeolite additions altered soil chemistry, we found the dominant effect to be a large increase in soil Na^{+} (Table 4). In addition, the zeolite increased soil Zn^{2+}, Fe^{2+}, Mn^{2+}, Cu^{2+}, exchangeable Mg^{2+}, exchangeable K, and NH_4^{+} ($P < 0.0001$, $P = 0.001$, $P = 0.001$, $P < 0.0001$, $P = 0.005$, $P = 0.02$, $P < 0.0001$, $P < 0.0001$, respectively) while decreasing exchangeable Ca^{2+} ($P = 0.05$).

Discussion

Our goal was to alter soil chemistry of a currently *B. tectorum*-dominated site in a way that allowed *B. tectorum* to germinate but which suppressed its emergence as ungerminated seeds may survive and germinate under different conditions. Since *B. tectorum* appeared to be P and K-limited, we targeted P-reducing ($CaCl_2$) and K-reducing ($MgCl_2$, NaCl and zeolite) soil amendments. Additionally, we were looking for soil amendments that are not only be useful for

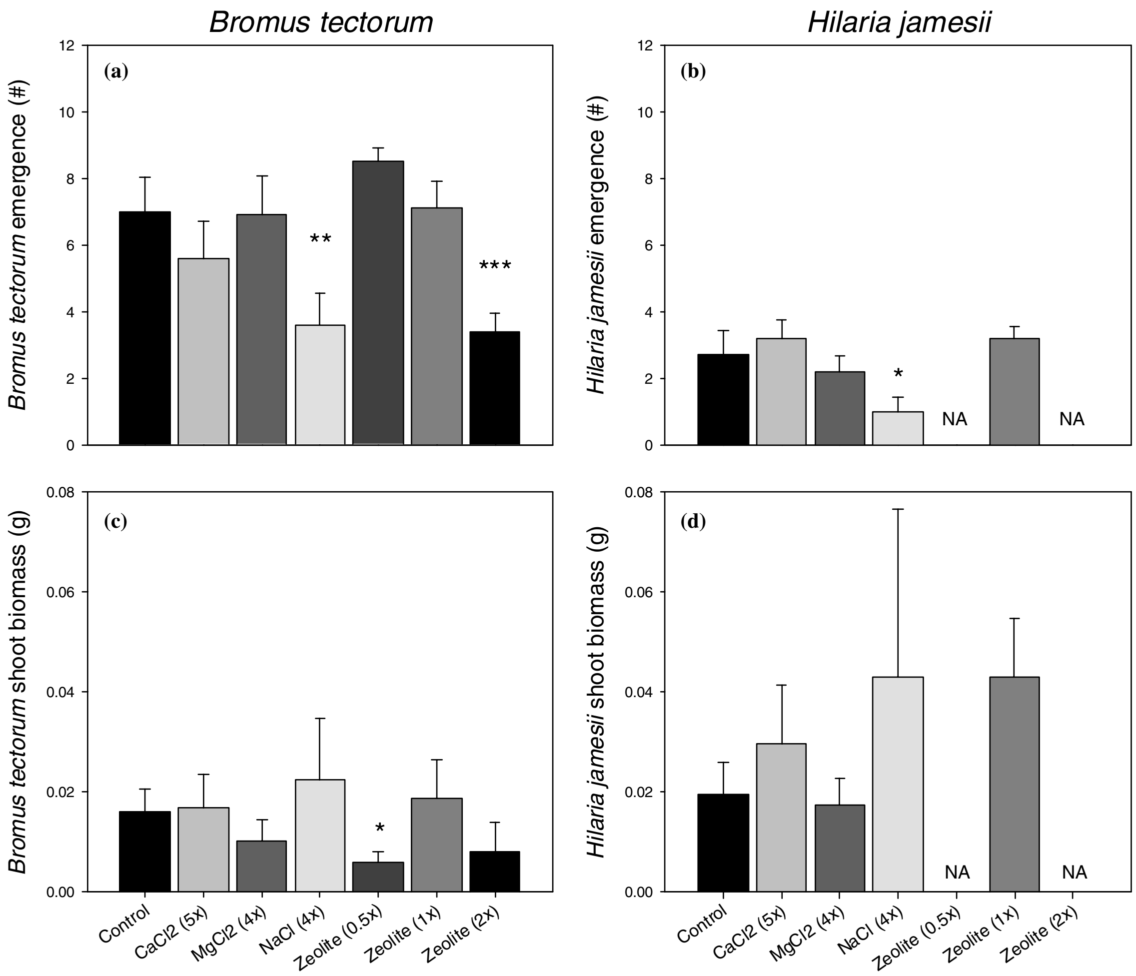

Figure 3. Effects of soil amendments on *Bromus tectorum* and *Hilaria jamesii* for Experiment 2. (a) Emergence (out of 10) for *B. tectorum*. (b) Emergence of *H. jamesii*. (c) Shoot biomass of *B. tectorum*. (d) Shoot biomass of *H. jamesii*. Numbers in parentheses signify amendment concentrations. Error bars represent ±1 standard error. $* = P \leq 0.10$; $** = P \leq 0.05$; $*** = P \leq 0.001$. NA (not appropriate) signifies treatments that were applied to *B. tectorum*, but not *Hilaria*.

controlling *B. tectorum* but other annual invaders as well. Crooke and Knight (1962) and Scott and Billings (1964) first noted that annual plants dominated soils with high K/Mg ratios, whereas perennial plants dominated soils with lower K/Mg ratios. Other studies have used K/Mg ratios to explain patterns of plant distribution in natural vegetation in the arid western US (Harner and Harper, 1973; McKnight et al., 1990; Pederson and Harper, 1979; Woodward et al., 1984).

Several of these soil amendments (5× $CaCl_2$, 4× $MgCl_2$, 4× NaCl, 0.5× zeolite, 1× zeolite, 2× zeolite) had negative effects on *B. tectorum* emergence and/or biomass in the field. However, the same amendment concentration did not always affect *B. tectorum* emergence and biomass similarly in the different experiments between years. For example, although the amendments and experimental set up were exactly the same, 5× $CaCl_2$, 4× $MgCl_2$, and 1× zeolite negatively affected *B. tectorum* in experiment 1 (2001–2002) during the drought year, but not during experiment 2 (2002–2003), which occurred in an average precipitation year. We propose that the higher rainfall during Experiment 2 may have leached these amendments more rapidly from the soil surface, and thus application levels may need to be adjusted to match precipitation levels.

Table 3. Mean values (± standard error) of exchangeable cations in soil of control and NaCl-treated soils from Experiment 1 after plants were harvested in the second year of the experiment

	Control	NaCl
Na^{+}	79	247***
±	4	24
Ca^{2+}	3690	3133**
±	77	133
Mg^{2+}	195	150**
±	9	6
K	267	204**
±	20	16

Units are μg nutrient/g soil.
** = $P \leq 0.05$; *** = $P \leq 0.0001$.

Changes in humidity and temperature may have also affected soil moisture and thus the transport of ions (Zeng et al., 2003).

Experiment 1 revealed interesting results regarding the residual effects of amendments, where the effects of certain amendments changed over time. The negative effect of 1× zeolite on *B. tectorum* emergence was lost after a year of leaching; however, the negative effects of 1× zeolite on *B. tectorum* biomass in the first year remained in the second year of the experiment. The effects of 4× $MgCl_2$ also changed over time, but in a surprising way. The addition of 4× $MgCl_2$ suppressed *B. tectorum* emergence in the first year, but after a year of leaching this amendment actually stimulated *B. tectorum* emergence. This amendment had no effect on *B. tectorum* biomass in the first year, but tended to also stimulate *B. tectorum* biomass a year after application. This result was unexpected and warrants further examination on the long-term effects of amendments.

Zeolite also had variable effects on *B. tectorum* depending on concentration. During the drought year, small amounts of zeolite greatly suppressed *B. tectorum* emergence. However, during the wetter year, much more zeolite was required to suppress *B. tectorum* emergence. The effects of zeolite on *B. tectorum* biomass were not consistent or predictable. Whereas 1× zeolite suppressed biomass during the drought year, only 0.5× was required during the wetter year, and larger additions had no effect. Another unexplainable result was the negative effect of 4× NaCl on *B. tectorum* emergence in the wetter year but not the drought year.

Since the goal of these amendments was to negatively affect *B. tectorum* and not the native *H. jamesii*, our results regarding the effects of the amendments on *H. jamesii* are of utmost importance. For example, the negative effects of 4× NaCl on *B. tectorum* emergence were also seen on *H. jamesii* emergence. Amendments that may reduce *H. jamesii* emergence are important to examine since *H. jamesii* already has a much

Table 4. Soil chemistry of samples in the zeolite laboratory experiment when zeolite and soil were soaked in deionized water or only soil soaked in deionized water

	Soil + water	Soil + water + zeolite	Percent change
Available P	5.8	6.2	7
Available K	84.3	85.9	2
Zn^{2+}	0.4	0.6***	50
Fe^{2+}	2.1	15.6**	642
Mn^{2+}	6.4	50.7**	692
Cu^{2+}	0.4	0.9***	125
Exchangeable Na^{+}	66	651***	886
Exchangeable Ca^{2+}	2937	2695**	−8
Exchangeable Mg^{2+}	127	146**	15
Exchangeable K	2.6	2.5***	177
NH_4^{+}	0.9	2.5***	177
NO_3	0.8	0.5	−40

Significant differences between soil + water + zeolite and soil + water treatments are significant at $P \leq 0.05$ (**) or $P \leq 0.0001$ (***). The third column represents the percent change for each nutrient due to the presence of zeolite. Percent changes are positive unless noted. Units are μg nutrient/g soil.

lower emergence rate than *B. tectorum*. Although 4× NaCl negatively affected *H. jamesii* emergence, it did not affect the biomass of newly established *H. jamesii* plants and may have even stimulated growth. Further experimentation examining the effects of these amendments on already established *H. jamesii* plants might also show no effect of the 4× NaCl amendment.

In this field study and the laboratory study of Belnap et al. (2003), zeolite was the most effective amendment in suppressing *B. tectorum* without negatively affecting *H. jamesii*. Our laboratory results found that zeolite decreased soil Ca^{2+}, but increased Zn^{2+}, Fe^{2+}, Mn^{2+}, Cu^{2+}, exchangeable Mg^{2+}, exchangeable K, NH_4^+ and especially large amounts of exchangeable Na^+ relative to ambient levels. Although these were statistically significant changes, we believe that the changes in Zn^{2+}, Fe^{2+}, Mn^{2+}, Cu^{2+}, exchangeable Na^+, and NH_4^+ are biologically significant. Additionally, although the change was not statistically significant, it is possible that the decrease in NO_3^- was biologically significant. It is unclear whether the increase in Zn^{2+}, Fe^{2+}, Mn^{2+}, Cu^{2+}, exchangeable Na^+, NH_4^+ or the decrease in NO_3^- was responsible for the negative effects of zeolite on *B. tectorum*.

Our laboratory experiment indicated that zeolite increased large amounts of beneficial micronutrients such as Fe^{2+}, Mn^{2+}, and Na^+; however, these micronutrients can also bind soil P and reduce P availability (Miller, 2000). We believe that Fe^{2+}, Mn^{2+}, and Na^+ did not bind P, as P increased slightly although it was insignificant. In addition, other studies have indicated that *B. tectorum* is limited by low soil Fe^{2+} and Mn^{2+} (R. Blank, personal communication), and thus adding these micronutrients would be more likely to stimulate growth than suppress it. We propose that the negative effects of zeolite were due to Na^+ toxicity, resulting from the very large amounts of Na^+ we added to the soil when using NaCl-loaded zeolite. Sodium is phytotoxic at high concentrations such as those we applied, as it can induce osmotic stress, inhibit enzyme activity, compete with K, and inhibit germination (Khan et al., 2000; Marschner, 1995; Mäser et al., 2002; Shen et al., 2003). Although zeolite appears to be a promising soil amendment, the time required to charge zeolite with Na^+ may decrease its feasibility for land managers.

We suggest that Na^+ soil amendments may be an excellent tool to suppress *B. tectorum*, as they successfully suppressed *B. tectorum* emergence and biomass and did not affect *H. jamesii* biomass. However, high levels of Na^+ suppressed *H. jamesii* emergence, which warrants further investigation. Na^+ soil amendments have the benefit of being inexpensive and easy to apply, but as with Mg^{2+}, Na^+ leaches quickly from soils. Thus, while Na^+ may suppress *B. tectorum* in the short term, it is possible it would eventually have no effect or even stimulate *B. tectorum*, as seen with Mg^{2+}. Therefore, long-term studies of Na^+ additions are required before this amendment is used to suppress *B. tectorum*.

In order for soil amendments to be an effective form of weed control, amendments must be inexpensive and easy to apply at large scales. In addition, amendments will likely be applied in plant communities where natives still exist and thus amendments need to have minimal effects on native plants. Our experiments highlight several soil amendments that can reduce *B. tectorum* emergence and biomass without negatively affecting *H. jamesii* in the field. However, the variability in effectiveness between years suggests that one must be cautious when applying them, as certain amendments may have negative effects on *B. tectorum* in one year but may have no effect or even stimulate *B. tectorum* in another year. Our results suggest that a further understanding of year-to-year variability, long-term effects, effects of soil type, and the effects of these amendments on other native microbial, plant and animal species within the community are necessary before implementing them as methods of control for *B. tectorum*.

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