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RESEARCH ARTICLE

Management of Non-Native Annual Plants to Support Recovery of an Endangered Perennial Forb, *Ambrosia pumila*

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Abstract

Invasive non-native plants pose a ubiquitous threat to native plant communities and have been blamed for the decline of many endangered species. Endangered species legislation provides legal instruments for protection, but identifying a general method for protecting endangered species by managing non-natives is confounded by multiple factors. We compared non-native management methods aimed at increasing populations of an endangered forb, *Ambrosia pumila*, and associated native plants. We compared the effects of a grass-specific herbicide (Fusilade II), hand-pulling, and mowing in two degraded coastal sage scrub sites in southern California, U.S.A. At both sites, hand-pulling had the greatest effect on non-native cover, and correspondingly resulted in the greatest increase in *A. pumila* stems. Fusilade II application also led to an increase in *A. pumila*, but was not as effective in controlling non-native plants as hand-pulling and its effect varied with the dominant non-native species. Mowing was not effective at promoting *A. pumila*, and its effect on non-native cover seemed to be related to rainfall patterns. Although some methods increased *A. pumila*, none of our treatments simultaneously increased cover of other native plants. Hand-pulling, the most effective treatment, is labor intensive and thus only feasible at small spatial scales. At larger scales, managers should take an experimental approach to identifying the most appropriate method because this can vary depending on the specific management objective (endangered species or whole native community), the dominant non-natives, yearly variation in weather, and the timing of treatment application.

Key words: **California, coastal sage scrub, *Erodium*, exotic plant, Fusilade, Mediterranean.**

Introduction

Invasive non-native plants pose serious threats to native plant communities worldwide and, after land conversion, are the most important cause of extinction (Vitousek et al. 1997; Chornesky & Randall 2003). In addition to altering ecosystem processes (Vitousek 1990; Mack & D'Antonio 1998) and reducing the economic and esthetic value of native ecosystems (Mack et al. 2000; Pimentel et al. 2000), invasive non-native plants can contribute to the loss of native plants through competitive interference (Hobbs & Atkins 1988; Carlsen et al. 2000). Therefore, it may be important to eliminate or decrease the abundance of non-native plants in order to maintain native plant populations, especially if the targeted, native plant species are already threatened or endangered.

Grassland ecosystems along with arid and semiarid shrub communities have been extensively invaded by non-native species. For example, a decline in native plant communities as a result of invasive non-native plants has been documented in coastal sage scrub (CSS) in California (Eliason & Allen 1997), an upland prairie in western Oregon (Wilson & Clark 2001), and in grasslands in Western Australia (Hobbs & Atkins 1988). Although these ecosystems are typically characterized by shrub and grass species, they also harbor a high diversity of forb species (Knapp et al. 2004); furthermore, forbs also represent a large proportion of endangered grassland species (Milberg 1994; Tibor 2001; Gillespie & Allen 2004). One such species is the federally endangered San Diego ambrosia (*Ambrosia pumila* [Nutt.] Gray; Asteraceae). *Ambrosia pumila* is a perennial forb that is restricted to southern California and north-central Baja California where it occurs in flood terraces of river drainages, valley bottomlands, open grasslands, and open areas in CSS habitat (Payne 1993; USFWS 2009). Historically, *A. pumila* was frequently observed in CSS throughout southern California; however, human activities

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(i.e. land development) have greatly reduced the extent of CSS in southern California and as a result it is one of the most endangered vegetation types in the United States (Rubinoff 2001). This transformation of CSS has severely reduced the amount of suitable habitat for *A. pumila*, and consequently there are currently only 15 remaining populations of *A. pumila* in the United States (USFWS 2009).

In addition to the reduction of CSS by human activities, competition with non-native plants also plays a significant role in the decline of *A. pumila*. For that reason, management practices aimed at controlling non-native plant species—such as mowing, hand-pulling, and herbicide application—may be necessary to maintain and restore the remaining populations of *A. pumila*. Mowing has previously been used in many plant communities to control non-native species, especially non-native grasses (Wilson & Clark 2001; Marushia & Allen 2011). However, the effects of mowing are extremely variable and the outcome is strongly influenced by the targeted species, the timing and intensity of mowing, and also by various abiotic factors (Proulx & Mazumder 1998; Wilson & Clark 2001). Herbicide application has proven to be effective against non-native plant species in CSS (Cox & Allen 2008), but repeated application of herbicides could simply shift the dominant non-native species to those that are resistant to herbicides (Hutchinson et al. 2007). Hand-pulling of non-native species, on the other hand, is an effective treatment against non-native species, yet this practice often disturbs the soil, which could lead to invasion by other non-native species (Rice 1985), and is very labor intensive.

This research was conducted to determine the most effective method to manage non-native plant species in order to restore populations of *A. pumila* while also promoting the native plant community in general. We examined the response of non-native plants, native plants, and *A. pumila* to three management practices aimed at controlling non-native species (mowing, hand-pulling of non-native species, and grass-specific herbicide application) on two sites in southern California. Because this study was replicated at two sites and over 2 years, we were able to examine the effectiveness of our management practices on plant communities with different dominant non-native species and over two growing seasons with different patterns of precipitation.

Methods

Study Sites

This study was replicated on two sites in southern California, U.S.A., within the extant range of *Ambrosia pumila*. The climate for both sites is Mediterranean with cool, wet winters and hot, dry summers. Precipitation generally occurs between November and April. Mission Trails (MT) is a 2,350-ha city-owned park located 13 km northeast of downtown San Diego. MT has an average temperature of 16.2°C and receives 225 mm of precipitation on average (CIMIS, Miramar, Station 150; data from 1999 to 2009). San Diego National Wildlife Refuge (SDNWR) is a 17,800-ha U.S. Fish and Wildlife Service national wildlife refuge located south of the city of Rancho San Diego. SDNWR has an average temperature of 16.3°C and receives an average of 180 mm of precipitation (CIMIS, Otay Lake, Station 147; data from 1999 to 2009). Both sites are characterized by CSS and chaparral plant communities.

Plant Species

Ambrosia pumila is a woolly gray-green herbaceous perennial plant species that occurs in isolated patches and spreads vegetatively by means of underground rhizome-like roots which give rise to aboveground stems (Payne 1993). This form of vegetative reproduction results in patches of aerial stems that may be members (ramets) of the same clone or may be genetically distinct clones (McGlaughlin & Friar 2007). Although *A. pumila* appears to primarily reproduce asexually, it is apparently still capable of sexual reproduction and a genetic study revealed relatively high genetic diversity when compared with other rare and endangered clonal species (McGlaughlin & Friar 2007). However, recent field collections have not provided evidence that viable seeds are produced (USFWS 2009).

Experimental Design

This study was initiated in February 2008. A randomized, complete-block design was used, with five blocks at each site. Blocks were superimposed over patches of *A. pumila* that had relatively uniform cover of *A. pumila* and ranged in size from 20 to 30 m^2. Each block consisted of twenty 1 m^2 plots with four treatments replicated five times. Treatments were randomly assigned and included mowing, hand-pulling of all non-native plants, application of Fusilade II (a grass-specific postemergent herbicide), and a control. The mowing treatment plots were cut using hand shears to a height of approximately 5 cm in early March of 2008 and 2009 at which time non-native grasses had begun to flower, but seeds had not matured. Mowed litter was left in the plots so as to replicate conditions that would be present after mowing on a large scale using power mowers. The hand-pulling treatment consisted of removing all non-native plant species during late February of 2008 and 2009 when the majority of plants had germinated and before seed maturation. For the herbicide treatment, Fusilade II (fluazifop P-Butyl; Syngenta Crop Protection, Greensboro, NC, U.S.A.) was applied to the entire 1 m^2 plot along with a non-ionic surfactant at a rate according to the labels in late February of 2008 and 2009. Control plots were left untouched during the course of this 2 year study.

Data Collection

Pre-treatment vegetation data was collected in February 2008 within 0.25 m^2 frames centered in the middle of each plot so as to limit any effects from adjacent treatments. We visually estimated the percent cover by each plant species as well as counted the number of *A. pumila* stems. Given the clonal nature of *A. pumila*, number of stems is not assuredly a reflection of number of genetically distinct individuals. Nevertheless, it reflects vegetative growth as well as any sexual reproduction, and thus is an indicator of species viability. Vegetation data collection was repeated in May 2008 (2 months after treatment), February 2009 (just before retreatment), and May 2009 (2 months after retreatment).

Statistical Analysis

We averaged the five replicates in each block and subsequently used these mean values to examine treatment effects on four response variables: non-native cover, native cover excluding *A. pumila*, the number of *A. pumila* stems, and *A. pumila* cover. To analyze the effect of sampling date, treatment, and site, as well as the interactions on each response variable, we used a three-way repeated measures multivariate analysis of variance (MANOVA). Differences among fixed factors were compared using post hoc tests with Bonferroni corrections. Differences among treatments within each site for each sampling date were analyzed using Tukey's honestly significant difference (HSD) at $p = 0.05$. At both sites, differences among sampling dates for each treatment were analyzed using a one-way repeated measures ANOVA. All data were analyzed for assumptions of normality and were transformed when necessary to satisfy these assumptions when required. All statistical analyses were performed using SPSS statistical software (v16.0, SPSS Inc., 2007).

Results

Percent Non-Native Cover

Averaged across all treatments and sampling dates, non-native cover was significantly higher at SDNWR (61.9 ± 3.3%) than at MT (56.4 ± 3.7%; $p < 0.05$; Table 1). Averaged across all sites and time periods, non-native cover also differed among treatments ($p < 0.001$), yet there was no significant interaction between site and treatment ($p = 0.20$; Table 1). Non-native plants at MT were characterized mainly by non-native grasses (*Bromus madritensis* L. and *Vulpia myuros* (L.) C. Gmelin), whereas non-native plants at SDNWR were primarily low-growing forbs (e.g. *Erodium botrys* (Cav.) Bertol.). A complete list of plant species found in experimental plots at MT and SDNWR is given in Table 2.

At both sites, there was no significant difference in non-native cover among treatments at the beginning of the experiment ($p > 0.05$; Fig. 1a & 1b). However, after treatments were applied in February 2008, there were significant differences in non-native cover among the different treatments. There was no change in non-native cover in the control among sampling dates at either site ($p > 0.05$; Fig. 1a & 1b). Mowing did not change non-native cover until the last sampling date at both sites, where it was significantly reduced by nearly 50% at MT ($p = 0.01$) and by roughly 30% at SDNWR ($p = 0.02$). At MT, non-native cover was significantly reduced following the first application of Fusilade II and hand-pulling in 2008 and remained lower compared with the control and pretreatment conditions for the remainder of the study ($p < 0.05$; Fig. 1a). Similarly, non-native cover was significantly reduced following the first application of Fusilade II and hand-pulling at SDNWR ($p < 0.05$), but non-native cover returned to pretreatment conditions by February 2009 in both treatments. After re-application of treatments in 2009, there was a significant reduction in non-native cover in the hand-pulling treatment ($p < 0.05$), whereas non-native cover did not change in the Fusilade II treatment (Fig. 1b). At the end of the experiment, there were significant differences in non-native cover among treatments at MT ($p < 0.001$; Fig. 1a), with non-native cover being significantly lower in hand-pulling and mowing treatments (3.3 ± 0.7% and 20.2 ± 5.0%, respectively) compared with the Fusilade II treatment (43.7 ± 7.7%), which had significantly lower non-native cover than the control (79.5 ± 3.5%). Non-native cover also differed significantly among treatments at SDNWR at the end of experiment ($p < 0.01$; Fig. 1b), with the hand-pulling treatment having significantly lower non-native cover (4.5 ± 0.7%) than Fusilade II and mowing treatments (52.8 ± 3.4% and 52.4 ± 6.9%, respectively), which had significantly lower non-native cover than the control (77.7 ± 3.2%).

Percent Native Cover

Averaged across all treatments and sampling dates, there was no difference in native cover, excluding *Ambrosia pumila*, between the two sites ($p = 0.19$). In general, native cover did not differ among treatments ($p = 0.28$) nor was there a significant interaction between site and treatment ($p = 0.86$; Table 1).

Table 1. Effects of sampling date, site, treatment and their interactive effects as revealed by three-way repeated measures MANOVA (F values, with p values in parentheses) on measures of non-native cover, native cover, *Ambrosia pumila* stems, and *A. pumila* cover.

	Between-Subject Effects			*Within-Subject Effects*			
Variables	*Site (S)*	*Treatment (T)*	*S × T*	*Sampling Date (SD)*	*SD × S*	*SD × T*	*SD × S × T*
Non-native cover (%)	**4.3 (0.046)**	**69.8 (<0.001)**	1.6 (0.201)	**92.0 (<0.001)**	**10.7 (0.006)**	**45.0 (<0.001)**	**2.7 (0.008)**
Native cover (%)*	1.8 (0.194)	1.3 (0.280)	0.3 (0.857)	1.6 (0.219)	**3.9 (0.018)**	**3.2 (0.002)**	0.9 (0.566)
Ambrosia stems (#)	**61.1 (<0.001)**	**13.3 (<0.001)**	**4.1 (0.014)**	**61.7 (<0.001)**	**8.7 (<0.001)**	**6.0 (<0.001)**	**2.8 (0.006)**
Ambrosia cover (%)	**62.0 (<0.001)**	**13.4 (<0.001)**	**4.1 (0.014)**	**87.1 (<0.001)**	**7.0 (0.001)**	**5.3 (<0.001)**	**2.2 (0.033)**

Values in boldface indicate statistical significance using Bonferroni corrections for between-subject effects and the Wilks' Lambda multivariate test for within-subject effects.
* Native cover does not include *A. pumila*.

Table 2. Plant species found (2008–2009) at Mission Trails Regional Park (MT) and San Diego National Wildlife Reserve (SDNWR).

Family	*Genus*	*Species*	*Life Span*	*MT*	*SDNWR*
Native plant species (= 25)					
Apiaceae	*Daucus*	*pusillus*	Annual	X	X
Asteraceae	*Corethrogyne*	*filaginifolia*	Perennial	X	X
Asteraceae	*Deinandra*	sp.	Annual	X	X
Asteraceae	*Isocoma*	*menziesii*	Perennial	X	
Boraginaceae	*Cryptantha*	sp.	Annual	X	X
Bryophyta	Moss		Perennial	X	X
Crassulaceae	*Crassula*	*tillae*	Annual	X	X
Cyperaceae	*Eleocharis*	sp.	Perennial	X	
Euphorbiaceae	*Croton*	*setigerus*	Annual	X	X
Fabaceae	*Lotus*	*hamatus*	Annual	X	X
Fabaceae	*Lotus*	*strigosus*	Annual	X	
Fabaceae	*Lotus*	*unifoliatus*	Annual	X	
Fabaceae	*Lupinus*	*bicolor*	Annual	X	X
Fabaceae	*Trifolium*	sp.	Annual	X	X
Gentianaceae	*Centaurium*	*venustum*	Annual	X	X
Juncaceae	*Juncus*	sp.	Annual		X
Liliaceae	*Calochortus*	sp.	Perennial	X	
Onagraceae	*Clarkia*	*purpurea*	Annual	X	
Poaceae	*Dichelostemma*	*capitatum*	Perennial	X	
Poaceae	*Distichlis*	*spicata*	Perennial	X	X
Poaceae	*Nassella*	*pulchera*	Perennial	X	X
Polygonaceae	*Eriogonum*	*fasciculatum*	Perennial		X
Portulacaceae	*Calandrinia*	*ciliata*	Annual	X	X
Scrophulariaceae	*Linaria*	*canadensis*	Annual	X	X
Violaceae	*Viola*	*pedunculata*	Perennial	X	
Non-native plant species (= 18)					
Asteraceae	*Centaurea*	*melitensis*	Annual	X	
Asteraceae	*Conyza*	sp.	Annual	X	
Asteraceae	*Filago*	*gallica*	Annual	X	X
Asteraceae	*Hypochoeris*	*glabra*	Annual	X	X
Asteraceae	*Lactuca*	*serriola*	Annual	X	X
Brassicaceae	*Brassica*	*geniculata*	Annual	X	X
Brassicaceae	*Sisymbrium*	*orientale*	Annual		X
Caryophyllaceae	*Silene*	*gallica*	Annual	X	X
Chenopodiaceae	*Salsola*	*tragus*	Annual		X
Fabaceae	*Medicago*	*polymorpha*	Annual		X
Geraniaceae	*Erodium*	sp.	Annual	X	X
Poaceae	*Avena*	sp.	Annual	X	X
Poaceae	*Bromus*	*diandrus*	Annual	X	X
Poaceae	*Bromus*	*hordeaceus*	Annual	X	X
Poaceae	*Bromus*	*madritensis*	Annual	X	X
Poaceae	*Hordeum*	sp.	Annual		X
Poaceae	*Vulpia*	*myuros*	Annual	X	X
Primulaceae	*Anagalis*	*arvensis*	Annual	X	X

The list is separated into native and non-native plant species. All species nomenclature follows *The Jepson manual: higher plants of California* (Hickman 1993).

At MT, there was no difference in native cover among treatments at the beginning of the study ($p = 0.80$), nor were there any changes in native cover within treatments among sampling dates ($p > 0.05$; Fig. 1c). Similarly, native cover did not differ among treatments at the beginning of the experiment at SDNWR ($p = 0.99$), nor were there any changes in native cover within treatments among sampling dates ($p > 0.05$; Fig. 1d). However, at the end of the study, native cover at SDNWR was significantly higher in the hand-pulling (7.0 ± 2.1%) compared with the mowing treatment (0.6 ± 0.2%; $p = 0.02$; Fig. 1d).

A. pumila Stems

Averaged across all treatments and sampling dates, the number of *A. pumila* stems was significantly higher at SDNWR (208.9 ± 16.4 stems/m^2) compared with MT (69.0 ± 6.3 stems/m^2; $p < 0.001$; Table 1). Averaged across all sites and sampling dates, the number of *A. pumila* stems differed among treatments ($p < 0.001$), and there was a significant interaction between site and treatment ($p = 0.01$; Table 1).

At both sites, there was no significant difference in the number of *A. pumila* stems among treatments before they were applied ($p > 0.05$; Fig. 2a & 2b). However, after treatments

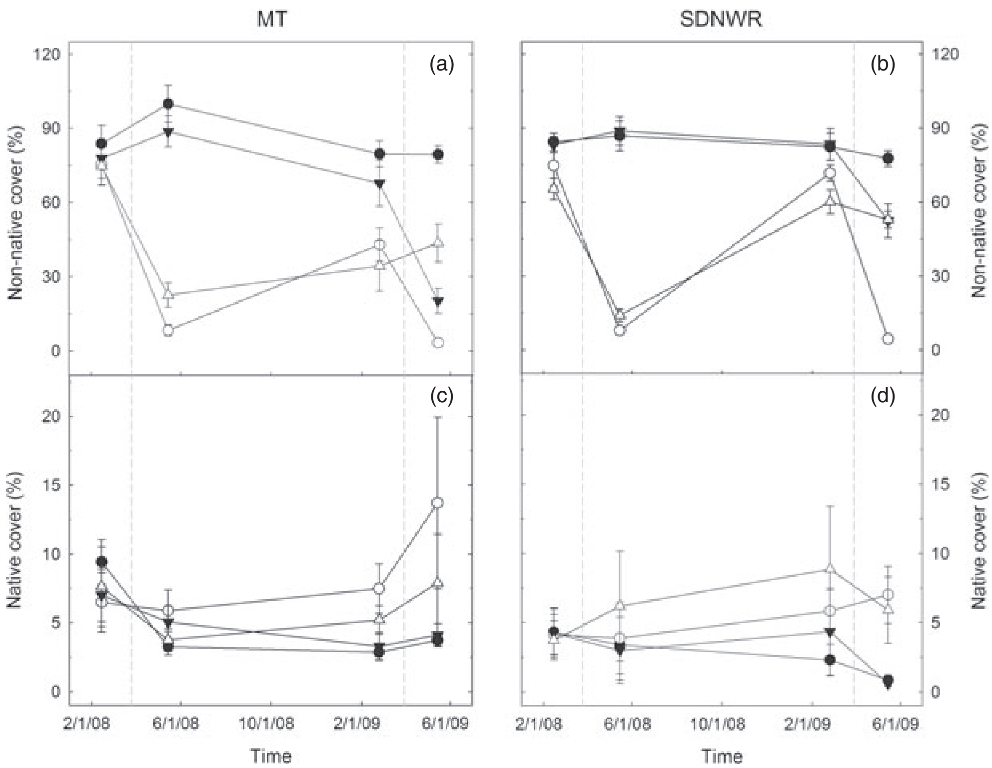

Figure 1. Mean (±SE) non-native cover (a, b) and native cover (c, d) among treatments at Mission Trails (left panels) and at San Diego National Wildlife Refuge (right panels). Treatments included the application of Fusilade II (△), hand-pulling (◯), mowing (▼), and a control (●). Timing of treatments is designated by vertical dashed lines. Native cover does not include *Ambrosia pumila*.

were applied in February 2008 there were significant differences in the number of *A. pumila* stems among treatments at both sites. Hand-pulling at MT significantly increased the number of *A. pumila* stems by about five times and remained higher throughout the study ($p = 0.04$), whereas the number of *A. pumila* stems did not differ among sampling dates in the other three treatments ($p > 0.05$; Fig. 2a). At SDNWR, the number of *A. pumila* stems significantly increased in hand-pulling and Fusilade II treatments after they were applied in 2008 and remained significantly higher compared with control and mowing treatments as well as pre-treatment conditions for the remainder of the study ($p < 0.05$; Fig. 2b). There was no change in *A. pumila* stems among sampling dates in control and mowing treatments at SDNWR ($p > 0.05$). At the end of the study, the number of *A. pumila* stems differed significantly at SDNWR ($p < 0.001$), with the number of *A. pumila* stems being significantly greater in hand-pulling and Fusilade II treatments (498.4 ± 61.3 stems/m^2 and 331.7 ± 46.2 stems/m^2; respectively) compared with the mowing treatment (123.2 ± 14.6 stems/m^2; Fig. 2b).

A. pumila Cover

Averaged across all treatments and sampling dates, *A. pumila* cover was significantly higher at SDNWR (15.4 ± 1.2%) compared with MT (5.9 ± 0.7%; $p < 0.001$; Table 1). Averaged across all sites and sampling dates, *A. pumila* cover differed among treatments ($p < 0.001$; Table 1), yet differences among treatments were only significant at SDNWR ($p < 0.001$).

At both sites, there were no significant differences in *A. pumila* cover before treatments were applied ($p > 0.05$; Fig. 2c & 2d). However, after treatments were applied in February 2008 there were significant differences in *A. pumila* cover among treatments at SDNWR ($p < 0.01$), but not at MT ($p = 0.13$). At SDNWR, *A. pumila* cover in Fusilade II and hand-pulling treatments significantly increased after treatments were applied in February 2008, yet returned to pre-treatment conditions by February 2009. After application of treatments in 2009, *A. pumila* cover in both treatments was again significantly higher compared with pre-treatment conditions ($p < 0.05$; Fig. 2d). At the end of the experiment, *A. pumila* cover differed significantly among treatments at SNDWR ($p < 0.001$), with *A. pumila* cover being significantly higher in Fusilade II and hand-pulling treatments (25.2 ± 3.9% and 35.8 ± 3.0%, respectively) compared with mowing and control treatments (9.0 ± 1.7% and 12.6 ± 1.9%, respectively).

Discussion

Although invasive non-native plant species are ubiquitous, it cannot be assumed that they are out competing native plant species without measuring the impacts of control techniques on both the non-natives and the native species. In this

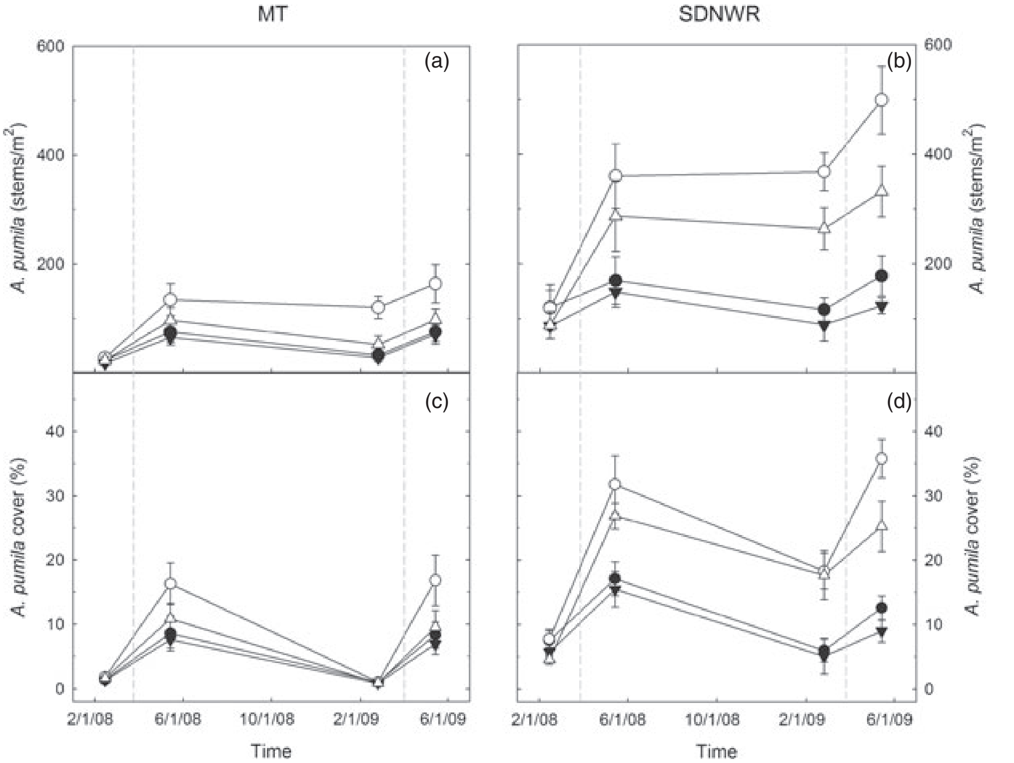

Figure 2. Mean (±SE) number of *Ambrosia pumila* stems (a, b) and *A. pumila* cover (c, d) among treatments at Mission Trails (left panels) and at San Diego National Wildlife Refuge (right panels). Treatments included the application of Fusilade II (△), hand-pulling (◯), mowing (▼), and a control (●). Timing of treatments is designated by vertical dashed lines.

study, competition from non-native plants appears to be a serious threat to the remaining populations of the endangered *Ambrosia pumila*, as shown by an increase in *A. pumila* stems when non-native plant cover was reduced. Other native plants, however, did not show a consistent response when non-natives were removed, suggesting that other limitations besides competition from non-natives may be affecting native plants at these sites. Given the varied responses of *A. pumila* and natives to the different treatments, the effectiveness of non-native management treatments seems to depend on a number of factors. Thus, one method of non-native plant treatment may not be effective in achieving a management objective of both increasing *A. pumila* and the native community.

Hand-pulling of non-native species resulted in the greatest increase in the number of *A. pumila* stems, more than doubling the number of stems compared to the control at the end of the study. This method was also the most effective at increasing native species richness in a comparison of weed control methods for an invasive grass in the eastern U.S. (Flory & Clay 2009). One explanation for a positive response of *A. pumila* to the hand-pulling treatment may be related to the fact that *A. pumila* is frequently observed in lightly disturbed areas, such as along roads and firebreaks (Payne 1993; USFWS 2009). Soils in the hand-pulling treatment were disturbed as a result of physically removing non-native species, which, in turn, may have created more favorable microsites for *A. pumila.* Alternatively, the increased amount of non-native litter in both the herbicide and mowing treatments might be responsible for the reduced response of *A. pumila* stems in these treatments relative to the hand-pulling treatment (data not shown; averaged over both sites at the end of study, the mean percent covers of litter for Fusilade II, mowing, and hand-pulling were 16.4, 51.8, and 1.1%, respectively). Previous studies have shown that litter is one significant way that non-native species alter the characteristics of the communities they invade (D'Antonio & Vitousek 1992; Eliason & Allen 1997; Mack & D'Antonio 1998). Increased amounts of litter on the soil surface can inhibit germination by reducing the amount of light at the soil surface (Eliason & Allen 1997), reducing soil moisture (Davis & Mooney 1985), as well as suppressing the emergence of seedlings by creating a physical barrier (Facelli & Pickett 1991). Such alterations in soil properties may favor the establishment of non-natives at the expense of *A. pumila.* Litter removal in addition to the application of herbicide and mowing may, therefore, be necessary to increase the recovery of *A. pumila* and promote native cover.

Fusilade II has been shown to be a very effective product for controlling invasive non-native grasses (Cox & Allen 2008; Marushia & Allen 2011). In this study, we also observed a considerable reduction in non-native cover after the first application of Fusilade II in 2008. However, after the first application, we observed a gradual increase in non-native cover in Fusilade II plots throughout the remainder of the study. Although Fusilade II is recognized as an effective product for controlling non-native grasses, results from this study as well as from previous studies indicate that some non-native grasses are not affected by Fusilade II (Bowran & Wallace 1996; Kelly et al. 2007). For instance, *Vulpia myuros* did not appear to be damaged by Fusilade II and, in fact, the percent cover of *V. myuros* increased considerably after the first application in 2008 (E. Hasselquist, unpublished data). This may be due to Fusilade II herbicide resistance by this genus (Yu et al. 2004). Thus, repeatedly spraying with the grass-specific herbicide, Fusilade II, may simply shift the dominant non-native species to either a grass or a forb not susceptible to Fusilade II.

We also observed that Fusilade II reduced the cover of broad-leaved forbs from the genus *Erodium*, although the ability of Fusilade II to kill *Erodium* species is not indicated on the product label. This finding is consistent with previous studies that have shown Fusilade II to kill *Erodium* species (Steers & Allen 2010). We also observed no evidence of negative effects of Fusilade II on *A. pumila* and/or the cover of native species. This result is very promising not only for the recovery of *A. pumila* but also for restoration in other arid and semiarid environments where *Erodium* species are abundant (Figueroa et al. 2004). However, it should be noted that caution must be used when applying Fusilade II, especially in situations where native grasses and/or native *Erodium* species occur.

Although mowing has been widely applied as a management practice aimed at controlling non-native species, results from this study suggest that mowing had very little effect on non-native cover, especially during the first year. One explanation for the lack of an effect in the mowing treatment may be due to the timing of mowing. We timed our mowing to when non-native grasses had begun to flower, but seeds had not matured, which is consistent with other studies (Wilson & Clark 2001; Cox & Allen 2008). For example, in an upland prairie in western Oregon, Wilson and Clark (2001) showed that mowing in late spring, just before seed maturation, was more effective at controlling *Arrenatherum elatius*, an invasive perennial grass, and increasing native cover than mowing in early spring. Additionally, variation in weather conditions between years may have had an effect on the effectiveness of the mowing treatment. In the first year of this study, there was a late rain event in May, after the application of the mowing treatment in early March. In the second year, there was no significant rainfall after the mowing treatment was applied. The late rain event may help to explain why non-native cover was not reduced in the mowing treatment during the first year of this study, but was in the second year. An additional mowing treatment later during the first year would have likely made the mowing treatment more effective and has proven effective in other studies in southern California (Marushia & Allen 2011). Thus, the timing of mowing is critical, but it may also need to be reapplied multiple times per year for it to be effective at reducing non-native cover.

Interestingly, native cover did not respond as strongly to our treatments as *A. pumila*. One explanation for the lack of response in native cover may be that the majority of native cover consisted of annual plants, which could be influenced by recruitment limitations that prevent native annuals from responding in the same way as the perennial forb, *A. pumila*. It may take more time than the short duration of this study to see a positive response of native annual plants to our treatments. For instance, in a removal experiment in Wyoming big sagebrush, Boyd and Svejcar (2011) found that it took 10 years for annual forbs and grasses to return to pre-treatment levels, whereas perennial forbs were unaffected by the removal treatment. Previous studies using non-native management methods have also reported mixed responses in native plant communities. For example, Bahm and Barnes (2011) showed that although non-native plant species were drastically reduced using imidazolinone herbicides, there was no response in native species. Others have shown that the void created by the removal of a targeted non-native plant species is quickly replaced by other non-native species (Choi & Pavlovic 1998; Stephens et al. 2009) and that native species may respond in different ways depending on the non-native management method (Lulow 2008). This study provides more evidence that the effectiveness of non-native management methods depends on a number of factors, namely (1) the specific management objective, (2) the dominant non-native species in the community, (3) year to year variation in weather, and (4) timing of treatment application.

In conclusion, we recommend an experimental approach aimed at controlling non-native species to restore populations of *A. pumila* and the native plant community. This approach should include some combination of mowing, application of herbicides, and/or litter removal depending on the dominant non-native competitors. We would also like to highlight that these management practices need to be monitored over longer time periods, in order to examine longer-term effects and to determine how climate variability and timing of treatment may affect the outcome of different management practices.

Implications for Practice

- For small areas, hand-pulling is likely the best management tool to restore *Ambrosia pumila* and promote natives. For larger areas, an integrative and investigative approach that combines different management practices is recommended.
- The widespread application of grass-specific herbicides could shift the dominant non-native species from *Bromus* spp. to *Vulpia myuros* or other non-native forbs that are resistant to the herbicide.
- Fusilade II, a grass-specific herbicide, is effective at controlling annual forbs from the genus *Erodium*.
- Timing of mowing is crucial for its effectiveness at reducing non-native cover. If there are late season rains, a second mowing may be necessary.
- Removal of dead biomass, or litter, after treatments are applied would likely improve conditions for native plant recovery.

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