

Altering Light and Soil N to Limit *Phalaris arundinacea* Reinvasion in Sedge Meadow Restorations

Basil V. Iannone III^{1,2,3} and Susan M. Galatowitsch²

Abstract

Efforts to eradicate invasive plants in restorations can unintentionally create conditions that favor reinvasion over the establishment of desired species, especially when remnant invasive propagules persist. Reducing resources needed by the invader for seedling establishment, however, may be an effective strategy to prevent reinvasion. Propagules of *Phalaris arundinacea* persist after removal from sedge meadow wetlands and reestablish quickly in posteradication conditions, hindering community restoration. A study was conducted in two experimental wetlands with controlled hydrologic regimes to determine if reducing light by sowing short-lived, nonpersistent native cover crops or immobilizing soil N by incorporating soil-sawdust amendments can prevent *Phalaris* reinvasion, allowing native communities to recover. A 10-species perennial target community and *Phalaris* were sown with high-diversity, low-diversity, or no cover crops in soils with or without sawdust, and seedling emergence, establishment, and growth were measured. High-diversity cover crops

reduced light, decreasing *Phalaris* and target community seedling establishment by 89 and 57%, respectively. Short-term nitrogen reduction in sawdust-amended soils delayed *Phalaris* seedling emergence and decreased *Phalaris* seedling establishment by 59% but did not affect total target community seedling establishment. The target community reduced *Phalaris* seedling establishment as effectively as cover crops did. In plots where the target community was grown, amending soils with sawdust further reduced *Phalaris* seedling growth but not establishment. Results show that use of cover crops can reduce seedling establishment of desired species and is counterproductive to restoration goals. Further, establishing target species is more important and practical for limiting *Phalaris* reinvasion than is immobilizing nitrogen.

Key words: competition, cover crops, invasion biology, resource availability, seedling establishment, soil amendments, wetland restoration.

Introduction

Eradicating invasive species can have unintended adverse effects on ecosystems (Zavaleta et al. 2001; Courchamp et al. 2003; Chapuis et al. 2004; Harms & Hiebert 2006). Often, eradication results in environmental conditions that promote reinvasion or new invasions (Morrison 2002; Ogden & Rejmánek 2005; Adams & Galatowitsch 2006; Hulme & Bremner 2006). Restoring native vegetation may not be possible if invasive propagules persist through eradication and resources required for their reestablishment are abundant (sensu Adams & Galatowitsch 2006). Alternatively, if native species establish before the invader, they can provide the restored ecosystem with resiliency against future invasions by sequestering available resources (Barger et al.

2003; Seabloom et al. 2003; Bakker & Wilson 2004). The availability of resources needed for plant establishment can affect final community composition (Grubb 1977; Schupp 1995; Eriksson 2002), making resource availability an important factor in restoration outcomes when propagules of both the invaders and the desired community are present.

Reed canarygrass (*Phalaris arundinacea* L.; hereafter *Phalaris*) is an invasive perennial grass in temperate North American wetlands (Galatowitsch et al. 1999a). Efforts to eradicate *Phalaris* from sedge meadow wetlands in the Midwestern United States leave these ecosystems prone to reinvasion (Adams & Galatowitsch 2006) because of remnant *Phalaris* seed banks and dispersal from nearby seed sources. Further, desired native plants are dispersion limited, and their establishment requires direct seeding (Kettenring 2006). Nonetheless, even when native plants are seeded, *Phalaris* dominates these ecosystems within two growing seasons because of its rapid growth and high reproductive capacity under moist, fertile posteradication conditions (Adams & Galatowitsch 2005, 2006). Limiting resources needed by *Phalaris* at early developmental stages may prevent reinvasions, thereby aiding restoration

¹ Department of Ecology, Evolution, and Behavior, University of Minnesota, 100 Ecology Building, 1987 Upper Buford Circle, St. Paul, MN 55108, U.S.A.

² Department of Horticultural Science, University of Minnesota, 305 Alderman Hall, 1970 Folwell Avenue, St. Paul, MN 55108, U.S.A.

³ Address correspondence to B. V. Iannone, email bianno2@uic.edu

efforts, if seeded native species are more competitive at lower resource levels (sensu Tilman et al. 1999).

Limiting light availability in sedge meadows after *Phalaris* eradication may prevent reinvasion. Because *Phalaris* seeds cannot germinate in the dark, intact wetland canopies reduce *Phalaris* establishment, and because of increased structural complexity, diverse canopies possibly block more light (Lindig-Cisneros & Zedler 2001, 2002a, 2002b). Sowing a rapidly growing native cover crop to reduce light availability, therefore, may prevent *Phalaris* reinvasions if seeded native species require less light for germination, seedling establishment, and growth (Galatowitsch et al. 1999b; Lindig-Cisneros & Zedler 2002a).

Studies of cover crop use in wetland restorations suggest that this strategy is ineffective because it might prevent the establishment of native graminoids, which have light requirements similar to those of *Phalaris* (Perry & Galatowitsch 2003, 2004). Yet, the only field study of cover crop use in wetland restorations considered competition between a single sedge meadow species, Bottlebrush sedge (*Carex hystericina* Muhl.), and *Phalaris* grown under two single-species cover crops (Perry & Galatowitsch 2003). No studies have investigated how multispecies cover crops affect light competition between *Phalaris* and a typical restoration seed mix.

Because native plants can suppress *Phalaris* seedling growth in low-nitrogen (N) environments (Perry et al. 2004), another resource-limiting strategy could be to reduce N after *Phalaris* eradication. Prairie pothole wetlands occur within agricultural landscapes, often receiving N inputs (Neely & Baker 1989; Brinson & Malvarez 2002). Increased N availability is responsible for the displacement of native vegetation by invasive species in other ecosystems (Dukes & Mooney 1999) and may be contributing to *Phalaris* outcompeting desired native wetland species (Green & Galatowitsch 2002; Lavoie et al. 2005).

Perry et al. (2004) tested if elevated soil N contributed to the competitive ability of *Phalaris* in a greenhouse experiment where *Phalaris* and *C. hystericina* were grown together in wetland soils under depleted and ambient inorganic N concentrations. Inorganic N was reduced by incorporating pine sawdust (i.e., carbon amendment), which caused microbial immobilization of N. *Carex hystericina* outcompeted *Phalaris* in plots with depleted N, suggesting that native seedlings had a greater capacity to attain and assimilate N than *Phalaris* seedlings in low-N environments (Perry et al. 2004). Reducing N by adding carbon to soils has been effective in limiting invasive species establishment in other ecosystems (Zink & Allen 1998; Blumenthal et al. 2003; Averett et al. 2004), but the effects of carbon amendments on soil N concentrations and the longevity of these effects in wetlands are unknown.

The purpose of this study was to determine if reducing light and N availability with cover crops and sawdust amendments is effective in preventing *Phalaris* seedling

establishment after its initial removal from invaded sedge meadows. Our objectives were to (1) determine the effectiveness of cover crops varying in structural complexity and sawdust amendments in reducing light and N availability, respectively; and (2) determine how these treatments affect seedling emergence, establishment, and growth of a target community seed mix and *Phalaris* in conditions resembling sedge meadow restorations after *Phalaris* removal.

Methods

Experimental Overview and Site Description

We designed a randomized complete block experiment with four factors. A 10-species target community seed mix (absent or present) and *Phalaris* (absent or present) were sown in plots with one of three cover crop treatments: high diversity (5 structurally different species), low diversity (1 species), or absent. These treatments were grown in soils with or without sawdust amendments. During October 2004, a row of 24-one m² plots were marked out at 1, 3, and 5 m distances from the water's edge on the western side of two experimental wetland basins. The 24 treatment combinations were randomly assigned to individual plots within each row (6 replicates blocked on both basin and distance from water).

The basins are located at the University of Minnesota Horticultural Research Center in Carver County, Minnesota, lat 44°51'45"N, long 93°36'00"W. The site, which historically was a drained depressional wetland used for agriculture, is classified as a Glencoe clay loam soil (Cumulic Endoaquoll). In 1994, the area was divided by earthen dikes into four approximately 0.20-ha basins with separate water inlets and adjustable drainage tiles to allow precise hydrological control in each basin.

Experimental Set Up and Sawdust Treatments

Site preparation began in fall 2004 by removing vegetation, and surveying and grading the study areas to make them uniform in elevation relative to the basin bottoms. Plots were re-surveyed prior to the start of the experiment. On 30 September 2004, Basamid soil fumigant (Dazomet; BASF Corp., Mt. Olive, NJ) was applied to deplete the seed bank. The following spring, weed fabric was affixed between plots to prevent vegetative growth in these areas, and fiberglass screen extending approximately 15 cm above and below the soil surface was installed around plots to prevent between-plot migration of seeds.

Sawdust was incorporated during October 2004 following Perry et al. (2004). In plots assigned "sawdust," the upper 7 cm of soil was removed and replaced with cedar (*Thuja* sp.) sawdust. Soil removal assured that all plots had similar soil volumes. Sawdust was hand tilled to a depth of 20 cm, resulting in a soil:sawdust ratio of 2:1 by

volume (8.40 ± 0.13 kg dry weight/plot). The sawdust, acquired from Serv-a-Dock, Inc. (Victoria, MN), was 49.9% C and 1.6% N with nitrate-N and ammonium-N concentrations of 15 and 141 mg/kg, respectively. Preliminary comparisons of chemical parameters (other than soil N) revealed no major differences between plots with or without sawdust (Iannone 2007). Soil-microbe recolonization was initiated by sprinkling 250 mL of water from an adjacent restored wetland through a 106- μ m sieve (to prevent introduction of nonexperimental seeds) over the soil in each plot. Soil removal and sawdust incorporation occurred 7 months prior to the start of the experiment, and reinoculation occurred 1 month prior to the start of the experiment.

Nitrate-N and ammonium-N were measured on soil samples collected 1 week prior to the start of the experiment from two randomly chosen plots (one with and one without sawdust) in each replication. All analyses of soil and sawdust chemistry were conducted at the University of Minnesota Research Analytical Laboratory (St. Paul, MN).

Cover Crop Treatments and Native Seeding

Five native species were chosen as cover crops; all were annuals or short-lived perennials so they would not be persistent competitors. We sought to create two different subcanopy light environments by using cover crop species that varied structurally (sensu Lindig-Cisneros & Zedler 2002a, 2002b). The high-diversity cover crop seed mix consisted of American sloughgrass (*Beckmannia syzigachne* (Steud.) Fern.), Fox sedge (*Carex vulpinoidea* Michx.), Bur-marigold (*Bidens cernua* L.), Dock-leaved smartweed (*Polygonum lapathifolium* L.), and Northern willow-herb (*Epilobium glandulosum* Lehm.) sown at equal densities. The low-diversity cover crop seed mix consisted solely of *B. syzigachne*. The target community seed mix consisted of 10 C_3 perennial species sown at equal densities (listed in Table 4). Target community species were selected from a seed mix commonly used in public restoration projects in Minnesota (Jacobson 2003); all are common and native to local sedge meadows. Nomenclature followed Gleason and Cronquist (1991).

Cover crop and target community seed mixes were sown at 2,100 and 2,250 viable seeds/m², respectively. Cover crop density was based on recommendations for public restoration projects in Minnesota (Jacobson 2003); target community density was based on seed bank densities of natural sedge meadows (Galatowitsch & Biederman 1998). *Phalaris* was sown at a density representative of a remnant *Phalaris* seed bank after eradication in restorations—60 viable seeds/m² (Adams & Galatowitsch 2006).

Prior to the experiment, seeds were tested for viability and cold stratified. Viability was estimated on 200 seeds of each species using tetrazolium analysis (Grabe 1970). Seeds were then stratified in moist, steam-sterilized wetland soil at 4°C for 4 months to mimic outdoor conditions

and aid in breaking dormancy (Baskin & Baskin 1998; Kettenring & Galatowitsch 2007). Seeds were sown on 4 and 5 May 2005.

Seeds were acquired from suppliers in Minnesota and Iowa. *Polygonum lapathifolium*, *E. glandulosum*, and *C. hystericina* were purchased from Prairie Moon Nursery (Winona, MN). *Beckmannia syzigachne* and *Phalaris* were donated by Shooting Star Native Seed (Spring Grove, MN) and the University of Minnesota, Department of Agronomy (St. Paul, MN), respectively. All other seeds were purchased from Ion Exchange, Inc. (Harper Ferry, IA).

Site Maintenance and Data Collection

Site maintenance consisted of manipulating water levels to mimic the hydrology of an adjacent restored wetland and weeding for 10 weeks after seeding. To determine treatment effects on N and light availability, we measured soil nitrate-N and ammonium-N at weeks 9 and 18, and the proportion of photosynthetically active radiation (PAR) blocked by plant canopies at weeks 7, 10, 13, and 16. All measurements were taken from the inner 0.8 m² of the plots to avoid edge effects. Soil nitrate-N and ammonium-N were measured on a moist, 3 g subsample taken from three homogenized 1.5-cm diameter \times 20-cm soil cores. Soil cores were collected from three random points in all plots of four randomly chosen replicates (two per basin). Nitrogen values were adjusted to account for soil moisture. The percentage of PAR blocked was estimated in all plots by dividing the average of two perpendicular ground-level PAR readings by an above-canopy PAR reading and subtracting the value from 1. PAR readings were made between 1100 and 1400 h on cloudless days using a line quantum sensor attached to a LI-250A light meter (LiCOR[®] Biosciences, Lincoln, NE).

Seedling emergence and establishment were estimated from shoot counts of all species taken from five randomly placed 10 \times 10-cm subplots, within each plot every 3 weeks. Cumulative proportion of seedling emergence was estimated during each sampling period by adding any increase that occurred in shoot density to the prior week's density and dividing this value by the number of viable seeds sown. This estimate was treated as a minimum value because unobserved seedling emergence and mortality likely occurred between sampling periods. We assumed that all seeds emerged when proportions reached 1.0; values greater than 1.0 resulted from clonal growth. Shoot densities at week 16 were considered final seedling establishment.

To estimate growth, individual species cover, total plant cover, and canopy heights were measured in all plots every 3 weeks. Cover of individual species was estimated using the following ordinal cover class system: 0 = 0%; 1 = less than 1%; 2 = 1–4%; 3 = 5–24%; 4 = 25–49%; 5 = 50–74%; and 6 = 75–100%. Total plant cover was visually estimated to 10% increments. To limit observer bias, one person made all cover estimates. Canopy height was

estimated by averaging the vegetation heights from 10 random points.

Statistical Analyses

Treatment effects on average soil nitrate-N and soil ammonium-N concentrations for the length of the study and on changes in soil nitrate-N and soil ammonium-N concentrations were determined by analysis of covariance (ANCOVA) on the averages and differences of values from weeks 9 and 18, respectively. Two outliers, having ammonium-N concentrations 5× and 19× greater than any other values in their treatment combinations, were removed from the analysis. A randomized mixed-effects model was used to determine treatment effects on the percentage of PAR blocked. Linear regression was used to test for a relationship between total vegetative cover from weeks 7 through 16 and percent PAR blocked. Cumulative *Phalaris* and total target community seedling emergence were analyzed for each sampling period using Kruskal–Wallis or Wilcoxon rank sum tests. ANCOVA and logistic regression were used to test for treatment effects on shoot densities and ordinal cover classes, respectively. Bonferroni adjustments were made for the whole-model test of individual target community species ($\alpha/10$). The effects of sawdust amendments on total vegetative cover for weeks 7 through 16 and canopy heights at week 16 were analyzed by Wilcoxon rank sum tests. Model terms and transformations used in analyses are given in the appropriate tables.

All statistical analyses were performed using JMP 6.0 (SAS Institute, Cary, NC, U.S.A.), except for PAR blocked, which was analyzed using “R” (R Development Core Team 2008). All models considered plot elevation as

a covariate because plot settling occurred between experimental set up and seeding. Differences were considered significant at $p < 0.05$ except for Bonferroni-adjusted test ($\alpha = 0.05/10$). Differences between treatment levels were determined using Tukey’s honestly significantly different test ($\alpha = 0.05$). For reporting, values were back transformed and expressed as mean \pm SE unless otherwise noted. Some significant model terms were not discussed if significant higher order interactions provided an explanation of the response.

Results

Soil N and Light Availability

Sawdust amendments initially reduced soil nitrate-N concentrations from 8.6 to 3.8 mg/kg (56%) and soil ammonium-N concentrations from 14.7 to 5.9 mg/kg (60%) (data not shown). These effects were short lived. After 9 weeks, differences between nitrate-N concentrations in plots with versus without sawdust amendments decreased to 25%, on average, and by the end of the experiment (week 18), were not observed ($F = 5.71$; $df = 1, 68$; $p = 0.02$) (Table 1). After 9 weeks, sawdust raised ammonium-N concentrations by 46% ($F = 32.52$; $df = 1, 66$; $p < 0.0001$). Ammonium-N was higher in most treatments with sawdust by week 9 and all treatments with sawdust by the end of the study (Table 1).

Vegetation strongly influenced soil N. Throughout the study, plots with low-diversity cover crops had 86 and 44% more ammonium-N than plots with high-diversity or no cover crops, respectively ($F = 3.45$; $df = 2, 66$; $p = 0.04$), and high-diversity cover crops marginally reduced nitrate-N concentrations by 16% ($p = 0.05$) (Table 1). The

Table 1. Mean soil ammonium-N and soil nitrate-N concentrations in plots with different vegetative treatment combinations grown in soils with and without sawdust amendments.*

Vegetation in Plot	$\bar{X} \text{NH}_4^+ \text{-N} \pm \text{SE (mg/kg)}$				$\bar{X} \text{NO}_3^- \text{-N} \pm \text{SE (mg/kg)}$			
	Plots Without Sawdust		Plots With Sawdust		Plots Without Sawdust		Plots With Sawdust	
	Week 9	Week 18	Week 9	Week 18	Week 9	Week 18	Week 9	Week 18
High-diversity, target community, <i>Phalaris</i>	12 \pm 7.4	1.7 \pm 0.2	7.1 \pm 2.3	3.2 \pm 1.2	6.8 \pm 0.9	11 \pm 1.8	6.7 \pm 1.2	13 \pm 1.9
High-diversity, target community	3.2 \pm 0.6	1.6 \pm 0.2	9.8 \pm 4.2	2.0 \pm 0.2	6.5 \pm 1.5	11 \pm 2.6	6.5 \pm 0.5	9.7 \pm 1.5
High-diversity, <i>Phalaris</i>	3.7 \pm 0.4	1.5 \pm 0.2	6.2 \pm 1.2	2.5 \pm 0.6	6.6 \pm 1.0	8.4 \pm 1.0	5.6 \pm 0.7	10 \pm 1.2
High-diversity	3.7 \pm 0.7	1.6 \pm 0.2	9.2 \pm 1.8	2.0 \pm 0.2	7.3 \pm 1.4	8.9 \pm 1.2	5.8 \pm 1.1	10 \pm 1.8
Low-diversity, target community, <i>Phalaris</i>	14 \pm 8.8	1.4 \pm 0.1	6.8 \pm 2.8	3.0 \pm 0.7	7.9 \pm 2.1	7.8 \pm 0.9	5.5 \pm 1.8	9.5 \pm 3.2
Low-diversity, target community	3.5 \pm 0.7	1.6 \pm 0.1	7.7 \pm 2.4	2.6 \pm 0.4	6.5 \pm 0.8	10 \pm 1.1	5.7 \pm 1.3	8.7 \pm 1.7
Low-diversity, <i>Phalaris</i>	16 \pm 11	2.8 \pm 0.8	20 \pm 12	4.4 \pm 1.8	7.3 \pm 0.6	14. \pm 3.1	4.9 \pm 1.3	10 \pm 2.1
Low-diversity	15 \pm 12	2.8 \pm 1.1	19 \pm 9.3	9.3 \pm 3.8	11 \pm 2.5	16 \pm 4.4	7.9 \pm 2.7	14 \pm 1.7
Target community, <i>Phalaris</i>	5.2 \pm 1.1	1.6 \pm 0.1	7.0 \pm 2.1	2.4 \pm 0.3	9.3 \pm 3.2	6.9 \pm 2.5	6.2 \pm 2.6	9.8 \pm 1.2
Target community	9.2 \pm 5.6	1.6 \pm 0.1	14 \pm 7.3	2.3 \pm 0.2	9.6 \pm 1.8	9.0 \pm 1.3	7.1 \pm 1.3	10 \pm 4.1
<i>Phalaris</i>	4.2 \pm 0.7	1.5 \pm 0.4	7.4 \pm 2.5	3.1 \pm 0.6	5.9 \pm 1.6	14 \pm 3.2	4.7 \pm 0.3	17 \pm 5.2
No vegetation	4.4 \pm 1.8	1.7 \pm 0.3	15 \pm 6.7	7.3 \pm 1.3	11 \pm 2.5	20 \pm 2.2	4.7 \pm 1.5	22 \pm 6.7
Weekly experimental $\bar{X} \pm \text{SE}$	8.1 \pm 1.7	1.8 \pm 0.1	11 \pm 1.6	3.3 \pm 0.5	7.9 \pm 0.5	11 \pm 0.8	6.0 \pm 0.41	12 \pm 0.97

* Values are from samples collected at the halfway-point (week 9) and the end of the growing season (week 18).

target community reduced nitrate-N by 16% across all treatments ($F = 10.04$; $df = 1, 68$; $p = 0.002$) and ammonium-N by 54% in plots with low-diversity cover crops ($F = 3.56$; $df = 2, 66$; $p = 0.03$; cover crops \times target community) (Table 1). By the end of the experiment, the target community reduced nitrate-N in plots with low-diversity and no cover crops by 35 and 52%, respectively ($F = 10.40$; $df = 2, 68$; $p = 0.0001$; cover crops \times target community) (Table 1). *Phalaris* reduced nitrate-N concentrations by 13% in all treatments ($F = 4.53$; $df = 1, 68$; $p = 0.04$) and ammonium-N by 27% in sawdust-amended plots ($F = 11.48$; $df = 1, 66$; $p = 0.001$; *Phalaris* \times sawdust) (Table 1).

There was a strong positive relationship between total vegetative cover and the proportion of PAR blocked ($R^2 = 0.91$; $p < 0.0001$), explaining the high number of significant model terms (Table 2). High-diversity cover crops reduced light availability by 69% throughout the experiment and 96% by the end of the experiment (Tables 2 & 3). Given that *B. cernua* dominated the canopy of the high-diversity cover crop (modal cover = 75–100%), the reduction in light availability caused by this treatment was not attributable to structural complexity. Modal covers of the remaining species in this treatment never exceeded 4%. The target community reduced light availability by 52% throughout the experiment and almost as much as high-diversity cover crops by the end of the experiment (90%) (time \times cover crops \times target community) (Tables 2 & 3). The effects of both low-diversity cover crops and *Phalaris* on light reduction were only detected when these treatments were grown alone (time \times cover crop \times target community \times *Phalaris*) (Tables 2 & 3).

Sawdust amendments indirectly affected light availability by reducing plant growth. Sawdust amendments decreased mean total cover from 60 to 32% ($\chi^2 = 81.52$; $df = 1$; $p < 0.0001$) throughout the experiment and final canopy height from 39 ± 2.5 to 23 ± 2.1 cm (41%) ($\chi^2 = 19.05$; $df = 1$; $p < 0.0001$). This decrease in growth in sawdust-amended plots reduced the amount of light that plant treatments blocked, while having the greatest impact on *Phalaris* and the low-diversity cover crop growing alone (time \times target community \times *Phalaris* \times sawdust; time \times cover crops \times sawdust) (Tables 2 & 3). By the end of the study, the ability of both the high-diversity cover crop and the target community to block light was less affected by sawdust (time \times cover crops \times target community \times sawdust) (Tables 2 & 3). In addition, as plot elevation increased, light reduction decreased, but by week 16 this relationship reversed (time \times elevation) (Table 2). Although significant, this relationship was weak.

Phalaris Seedling Emergence, Establishment, and Growth

Reducing light availability did not delay *Phalaris* seedling emergence, but sawdust amendments and growth of the target community did. By week 7, all seeded *Phalaris* emerged in plots with high-diversity and no cover crops (Fig. 1A). *Phalaris* seedling emergence was delayed in

Table 2. Results of randomized mixed-effects model analysis for percentage of PAR blocked.*

Model Term	df	p Values
Basin	1	—
Distance from water	2	—
Elevation	1	0.001
Cover crops	2	<0.0001
Target community	1	0.0004
<i>Phalaris</i>	1	0.07
Sawdust	1	—
Cover crops \times target community	2	0.05
Cover crops \times <i>Phalaris</i>	2	—
Cover crops \times sawdust	2	<0.0001
Target community \times <i>Phalaris</i>	1	0.02
Target community \times sawdust	1	—
<i>Phalaris</i> \times sawdust	1	—
Cover crops \times target community \times <i>Phalaris</i>	2	—
Cover crops \times target community \times sawdust	2	0.07
Cover crops \times <i>Phalaris</i> \times sawdust	2	—
Target community \times <i>Phalaris</i> \times sawdust	1	0.02
Cover crops \times target community \times <i>Phalaris</i> \times sawdust		<i>Error term</i>
Time	1	—
Time \times elevation	1	0.0007
Time \times cover crops	2	0.009
Time \times target community	1	<0.0001
Time \times <i>Phalaris</i>	1	<0.0001
Time \times sawdust	1	—
Time \times cover crops \times target community	2	<0.0001
Time \times cover crops \times <i>Phalaris</i>	2	0.003
Time \times cover crops \times sawdust	2	<0.0001
Time \times target community \times <i>Phalaris</i>	1	<0.0001
Time \times target community \times sawdust	1	—
Time \times <i>Phalaris</i> \times sawdust	1	0.0009
Time \times cover crops \times target community \times <i>Phalaris</i>	2	0.02
Time \times cover crops \times target community \times sawdust	2	0.07
Time \times cover crops \times <i>Phalaris</i> \times sawdust	2	—
Time \times target community \times <i>Phalaris</i> \times sawdust	1	0.0009
Time \times cover crops \times target community \times <i>Phalaris</i> \times sawdust		<i>Error term</i>
Residual	525	
Total	575	

*Basin and distance from water were included into the model as random effects. Time was included as a continuous variable. Values were arcsine square root transformed prior to analysis. Only significant or marginally significant values are shown. Values in italics are marginally significant ($0.10 > p > 0.05$).

plots with low-diversity cover crops (Fig. 1A). Although sawdust had short-lived effects on soil N, and the effects of the target community on resource levels were not pronounced until later in the study (Tables 1 & 3), both treatments delayed *Phalaris* seedling emergence (Fig. 1B & 1C).

No treatment completely prevented *Phalaris* seedling emergence, but they did affect the extent of seedling establishment. *Phalaris* seedling establishment was reduced 87% by high-diversity cover crops (420 ± 120 to 51 ± 14 shoots/m²) and 81% by low-diversity cover crops

Table 3. The mean percentage of PAR blocked by different vegetative treatment combinations grown in plots with and without sawdust amendments.*

Vegetation in Plot	% PAR Blocked \pm SE							
	Plots Without Sawdust				Plots With Sawdust			
	Week 7	Week 10	Week 13	Week 16	Week 7	Week 10	Week 13	Week 16
High-diversity, target community, <i>Phalaris</i>	68 \pm 8.6	83 \pm 4.1	93 \pm 2.2	99 \pm 0.24	19 \pm 10	37 \pm 11	65 \pm 10	93 \pm 2.3
High-diversity, target community	73 \pm 9.4	83 \pm 5.6	93 \pm 1.5	98 \pm 0.62	10 \pm 3.6	43 \pm 4.9	70 \pm 4.6	96 \pm 11
High-diversity, <i>Phalaris</i>	66 \pm 9.3	83 \pm 3.6	90 \pm 1.2	98 \pm 0.76	13 \pm 2.9	35 \pm 5.8	69 \pm 6.6	93 \pm 3.2
High-diversity	70 \pm 6.8	78 \pm 7.2	91 \pm 2.0	97 \pm 0.60	8.7 \pm 3.6	30 \pm 3.2	62 \pm 6.0	91 \pm 2.7
Low-diversity, target community, <i>Phalaris</i>	18 \pm 4.5	39 \pm 5.1	69 \pm 6.7	93 \pm 1.9	4.0 \pm 1.7	7.1 \pm 1.4	34 \pm 3.4	84 \pm 4.2
Low-diversity, target community	12 \pm 0.81	45 \pm 8.7	73 \pm 4.3	94 \pm 1.6	4.9 \pm 2.1	9.1 \pm 4.3	28 \pm 8.6	65 \pm 9.6
Low-diversity, <i>Phalaris</i>	8.7 \pm 2.3	27 \pm 7.9	45 \pm 7.9	62 \pm 7.0	3.1 \pm 1.8	2.0 \pm 0.21	1.9 \pm 1.3	9.3 \pm 4.1
Low-diversity	18 \pm 7.4	33 \pm 11	43 \pm 11	59 \pm 8.1	5.7 \pm 4.4	5.1 \pm 3.1	9.6 \pm 5.0	15 \pm 5.3
Target community, <i>Phalaris</i>	16 \pm 5.6	47 \pm 6.7	80 \pm 4.2	97 \pm 0.58	1.8 \pm 0.80	5.9 \pm 1.9	27 \pm 6.1	85 \pm 5.9
Target community	8.6 \pm 3.7	37 \pm 3.6	78 \pm 4.1	95 \pm 1.4	4.4 \pm 1.5	6.0 \pm 3.0	27 \pm 3.5	84 \pm 5.0
<i>Phalaris</i>	8.4 \pm 1.5	23 \pm 5.4	53 \pm 5.9	76 \pm 2.9	0.58 \pm 0.54	1.4 \pm 0.61	1.2 \pm 0.71	6.4 \pm 2.1
No vegetation	0.0 \pm 0.80	0.0 \pm 1.8	0.1 \pm 1.1	2.0 \pm 0.63	0.0 \pm 0.76	0.0 \pm 0.78	1.0 \pm 1.2	1.0 \pm 1.1
Weekly experimental $\bar{X} \pm$ SE	31 \pm 3.7	48 \pm 3.6	67 \pm 3.5	81 \pm 3.4	6.3 \pm 1.2	15 \pm 2.2	33 \pm 3.4	60 \pm 4.7

* Starting at week 7, measurements were made every 3 weeks during the growing season.

(420 \pm 120 to 81 \pm 21 shoots/m²) compared to plots without cover crops ($F = 5.23$; $df = 2, 54$; $p = 0.008$). Sawdust amendments reduced *Phalaris* seedling establishment by 61% (260 \pm 82 to 100 \pm 35 shoots/m²) compared to plots without sawdust amendments ($F = 7.83$; $df = 1, 54$; $p = 0.007$). In addition, the target community reduced *Phalaris* establishment as much as cover crops did ($F = 5.12$; $df = 2, 54$; $p = 0.009$; cover crops \times target community). Sawdust had no effect on *Phalaris* shoot density in plots where the target community was present.

Phalaris growth was highest when growing alone in plots without sawdust amendments (Fig. 2B). Under these conditions, *Phalaris* cover was greater than 50% ($\chi^2 = 15.61$; $df = 2$; $p = 0.0004$; cover crops \times target community \times sawdust). Cover crops reduced the maximum cover of *Phalaris* from greater than 75% to less than 24%, with *Phalaris*' modal cover classes being 3 (5–24%) and 2 (1–4%) in plots with low- and high-diversity cover crops, respectively ($\chi^2 = 32.08$; $df = 2$; $p < 0.0001$). Sawdust reduced *Phalaris* growth, which decreased maximum *Phalaris* cover from greater than 75% to less than 24% ($\chi^2 = 56.13$; $df = 1$; $p < 0.0001$). The target community reduced *Phalaris* growth as much as cover crops did ($\chi^2 = 26.92$; $df = 2$; $p < 0.0001$; cover crop \times target community) (Fig. 2A) but not as much as sawdust amendments. *Phalaris* growth was most reduced in plots having both sawdust amendments and the target community present ($\chi^2 = 7.71$; $df = 1$; $p = 0.006$; target community \times sawdust) (Fig. 2A & 2B).

Target Community Seedling Emergence, Establishment, and Growth

Decreasing light reduced target community seedling emergence. By the end of the experiment, high-diversity cover

crops reduced target community seedling emergence from 0.61 \pm 0.03 to 0.33 \pm 0.02 (Fig. 3A). Low-diversity cover crops only delayed seedling emergence, whereas initial N reduction in sawdust-amended plots and competition from *Phalaris* had no effects (Fig. 3A–C).

Cover crops greatly reduced target community seedling establishment. By lowering densities of *Calamagrostis canadensis*, *Carex scoparia*, *Scirpus atrovirens*, and *Glyceria grandis*, both the high- and the low-diversity cover crops decreased total graminoid establishment, on average, by 73 and 32%, respectively (Tables 4 & 5 panel A). Although cover crops did not affect individual forb species, total forb establishment was marginally reduced by high-diversity cover crops ($p = 0.06$) (Tables 4 & 5 panel A). High-diversity cover crops reduced total target community establishment by 57% (Tables 4 & 5 panel A). High-diversity cover crops had less effect on forb versus graminoid seedling establishment, resulting in forbs representing a higher percentage of the established target community in plots with high-diversity cover crops (66%) versus plots with low-diversity (47%) or no cover crops (49%).

Phalaris and sawdust amendments had little effect on target community establishment. Although sawdust amendments reduced *C. canadensis* and *G. grandis* establishment, they had no effect on total graminoid or target community establishment (Tables 4 & 5 panel A). Sawdust amendments did, however, reduce total forb establishment by 46% in plots with low-diversity cover crops, decreasing their percentage in the target community from 60 to 36% (cover crops \times sawdust) (Tables 4 & 5 panel A). When *Phalaris* was present without cover crops, total forb establishment more than doubled, increasing the percentage of forbs in the target community from 32 to 48% (cover crops \times *Phalaris*) (Tables 4 & 5 panel A).

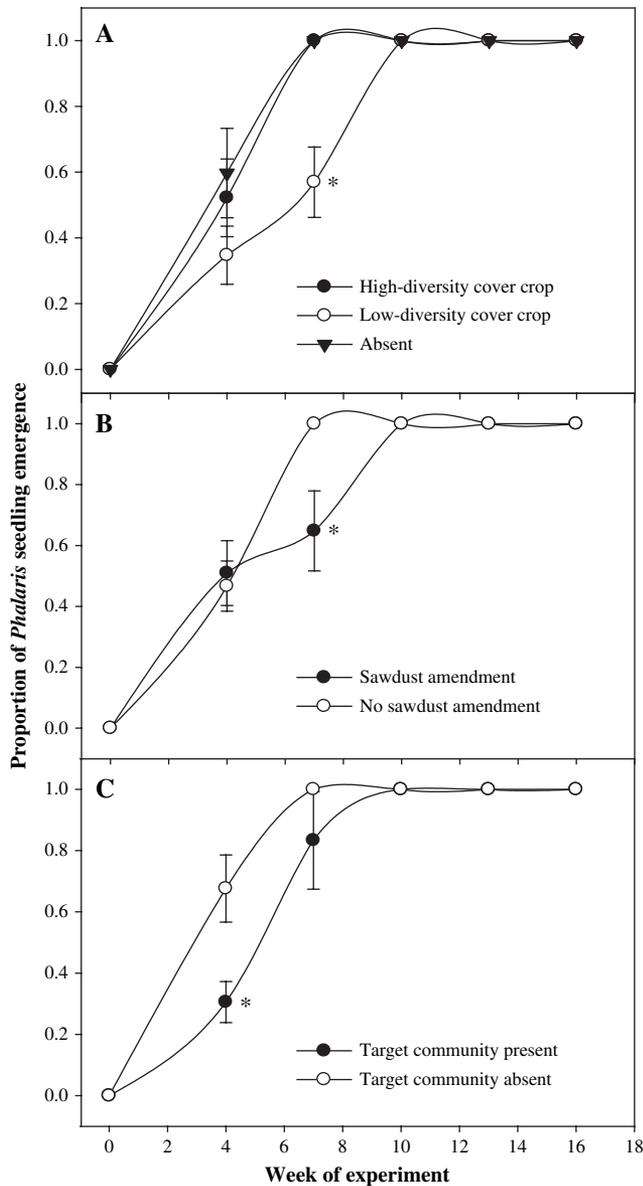


Figure 1. The effects of cover crops (A), sawdust amendments (B), and target community (C) on the cumulative proportion of *Phalaris* seedling emergence. Proportions that were greater than 1.0 were graphed as 1.0 with no SE bars. Data points with an asterisk (*) next to them signify that the point is significantly different from the other data points at that particular week, based on $p < 0.05$.

Use of cover crops reduced the growth of more target community species than sawdust did (Tables 5 panel B & 6). High-diversity cover crops had the greatest impact, lowering the modal cover classes of *C. scoparia*, *S. atrovirens*, *Mimulus ringens*, *Vernonia fasciculata*, *Pycnanthemum virginianum*, and *Eupatorium maculatum* by 1–3 classes (Table 6). Low-diversity cover crops reduced *C. scoparia* and *S. atrovirens*' modal cover classes from 3 (5–24%) to 2 (1–4%). Only *M. ringens* experienced decreased growth due to sawdust amendments (Table 6). In plots

with high-diversity cover crops, *V. fasciculata*'s modal cover increased from 3 to 4 (25–49%) if sawdust was added (cover crops \times sawdust) (Table 5 panel B) but decreased from 4 to 3 when *Phalaris* was present (cover crop \times *Phalaris*) (Table 5 panel B). Other significant interaction terms regarding individual target community species growth involved species whose modal cover class never reached greater than 2 or marginally significant results (Table 5 panel B).

Analyses revealed block and covariate effects on target community establishment and growth (Table 5). Forb establishment was 22% higher in one basin. As plot elevation increased, the growth of two species decreased. The growth of three species also varied by block (basin \times distance from water). Although significant, these effects were trivial to experimental outcomes.

Discussion

Developing effective restoration strategies that rely on cover crops and soil amendments will be difficult although they effectively reduce resource levels. Only high-diversity cover crops reduced light availability, but in doing so, they prevented native community establishment. This reduction in light availability likely resulted from the dominance of the broad-leaved species *B. cernua* rather than structural complexity. In addition to structural complexity, Lindig-Cisneros and Zedler (2002a, 2002b) noted the importance of broad-leaved species in reducing light availability. Because low-diversity cover crops blocked little light, their effects on target community and *Phalaris* seedling emergence, establishment, and growth were likely attributable to competition for another resource. Cedar sawdust depleted inorganic N in the short term but later increased ammonium-N. A study conducted at the same site, however, revealed that sawdust with higher C:N ratios than cedar reduced nitrate-N longer (Iannone 2007). Therefore, practitioners using sawdust for *Phalaris* control must time seeding with potentially short-lived periods of N depletion and should choose sawdust with high C:N ratios.

The increased soil ammonium-N concentrations caused by sawdust amendments may have important implications for restoration outcomes. The cedar sawdust used had a low C:N ratio (cedar C:N \approx 31) and high ammonium-N concentrations, possibly explaining the increase of ammonium-N in the soil. Perry et al. (2004) also noted an increase in ammonium-N using pine sawdust with a higher C:N ratio than the sawdust used in our study (pine C:N \approx 187). Given that increasing resources can affect competition and invasion (Tilman 1982; Johnstone 1986; Davis et al. 2000), elevated ammonium-N in sawdust-amended soils suggests that using sawdust as *Phalaris* control may alter plant communities and increase the invasibility of restored wetlands. Reduced vegetative growth, despite elevated ammonium-N, may be explained by the timing of N

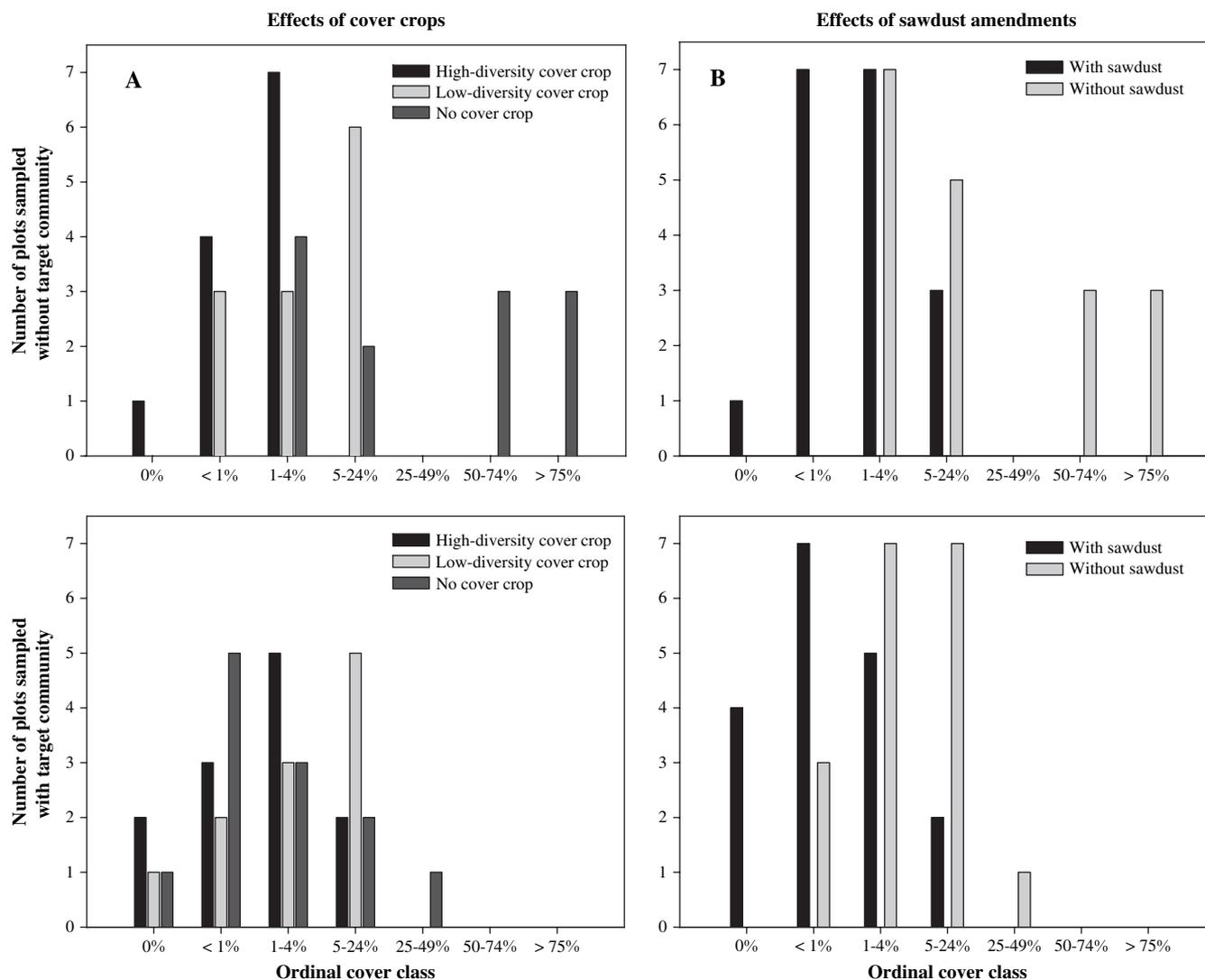


Figure 2. The effects of cover crops (A) and sawdust amendments (B) on *Phalaris* growth in plots without and with target community. The values graphed are the number of plots sampled with that particular ordinal cover class. $N = 72$.

depletion in sawdust-amended plots, which occurred early in the growing season when C_3 species typically exhibit high productivity (Ode et al. 1980).

Phalaris seedling emergence, establishment, and growth were limited more by N than light. Cover crops did not establish fast enough to achieve the intended goal of preventing *Phalaris* germination, which occurs after short photoperiods (Lindig-Cisneros & Zedler 2001). In contrast, *Phalaris* seedling emergence was delayed in plots with sawdust amendments. Both cover crops and sawdust amendments reduced *Phalaris* seedling establishment. *Phalaris* seedlings grown with high-diversity cover crops, however, reached similar shoot lengths as seedlings growing alone and greater shoot lengths than seedlings growing in sawdust-amended plots (Iannone unpublished data). These results suggest that although reducing either light or N can limit *Phalaris* seedling establishment, only N

reduction will slow *Phalaris* seedling emergence and limit *Phalaris* seedling growth.

In contrast to *Phalaris*, target community seedling emergence, establishment, and growth were limited more by light than N. Both cover crop treatments either reduced or delayed target community seedling emergence, whereas sawdust amendments did not. The low-light environment below high-diversity cover crops may explain reduced seedling emergence because *Carex* spp. need long photoperiods to germinate and because high levels of far-red light typical of dense plant canopies can reverse germination induction (Kettenring et al. 2006). In addition, target community seedling establishment and growth were reduced more by high-diversity cover crops than sawdust amendments. These results confirmed predictions that reducing light availability with cover crops will prevent native species establishment (Perry & Galatowitsch 2003,

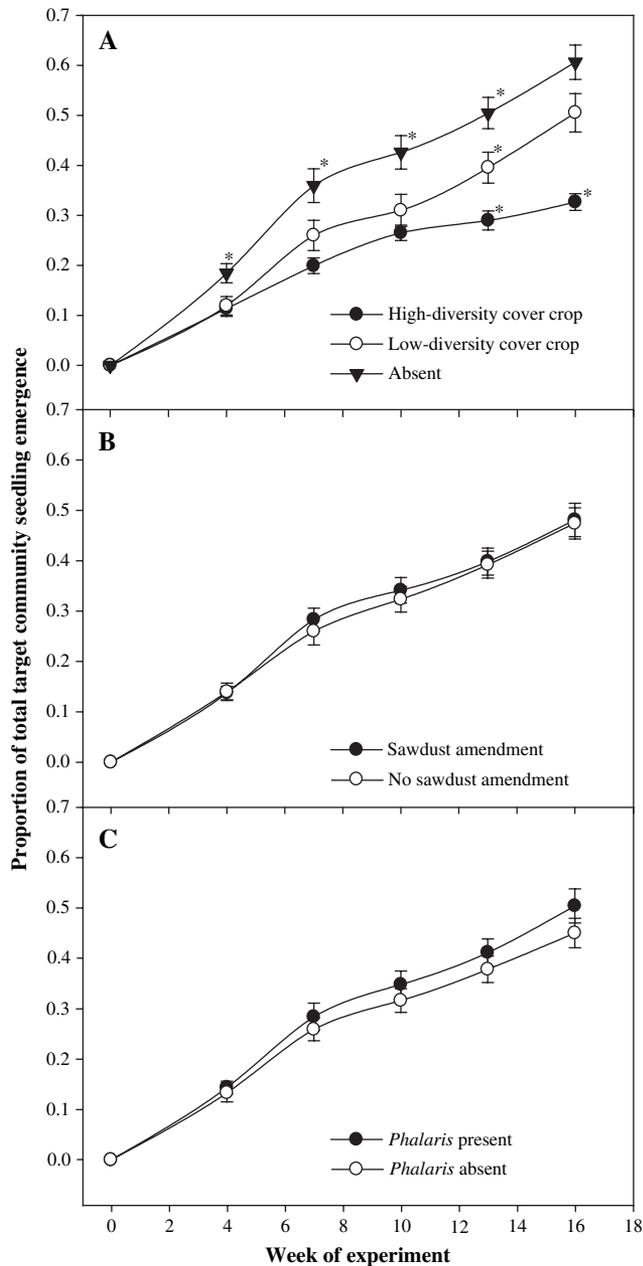


Figure 3. The effects of cover crops (A), sawdust amendments (B), and *Phalaris* (C) on the proportion of total target community seedling emergence. Data points with an asterisk (*) next to them are significantly different from the other data points at that particular week, based on $p < 0.05$.

2004). Sawdust amendments did, however, reduce native grass establishment, which has been noted in other studies (Averett et al. 2004; Eschen et al. 2007) and suggests that practitioners using sawdust should expect species-specific rather than community-level responses (Eschen et al. 2006).

The target community reduced *Phalaris* reinvasion. This result was unexpected because *Phalaris* typically out-

competes wetland species (Wetzel & van der Valk 1998; Green & Galatowitsch 2002; Adams & Galatowitsch 2006). These findings may be attributed to sowing densities and cold stratification of target community seeds. Most restoration seed mixes contain about 75% less perennial seeds than that used in this study (Jacobson 2003). High seed densities and cold stratifying seeds likely increased germination and establishment rates (Schütz & Rave 1999; Sheley & Half 2006; Kettenring & Galatowitsch 2007). Once established, the target community reduced light and N availability. Additionally, the broad-leaved forb *V. fasciculata* established at high densities, possibly further reducing light. The ability of the target community to reduce *Phalaris* seedling establishment and both light and N availability suggest that reducing resources by establishing perennial species is vital to preventing *Phalaris* reinvasion (sensu Barger et al. 2003; Seabloom et al. 2003; Bakker & Wilson 2004).

Experimental treatments not only affected target community seedling emergence, establishment, and growth, but also affected community composition. The established target community had a higher proportion of forb seedlings in plots with *Phalaris* and in plots with both non-amended soils and low-diversity cover crops. This suggests that these treatments competed more with graminoids than with forbs and that restorations using grass cover crops or lacking follow-up *Phalaris* control may result in forb-rich communities atypical of natural sedge meadows (Galatowitsch & van der Valk 1996). High forb abundance, however, in a sedge meadow restoration where grass cover crops were not used and *Phalaris* control was ongoing suggests that a forb-rich community may be a typical transitional state in the development of restored sedge meadow communities (Bohnen & Galatowitsch 2005).

Conclusions

Establishing perennial vegetation rapidly may be more important than reducing initial resource availability in preventing *Phalaris* reinvasion. The ability of native species to reduce *Phalaris* seedling establishment may be attributed to sowing native perennial species at higher than typical densities and cold stratifying seeds prior to sowing, which likely increased rates of germination, establishment, and resource sequestration. Cover crops failed to impede *Phalaris* germination and prevented target community seedling establishment. Therefore, cover crops should not be used. Given the short-lived effects that sawdust had on N depletion and that sawdust did not reduce *Phalaris* seedling establishment more than the target community did, the logistical difficulties of using sawdust may outweigh the benefits. However, because amending soils with sawdust further reduced *Phalaris* growth in plots where the target community was grown and the short-lived effects of sawdust on N depletion may have resulted from the sawdust species used, N reduction deserves

Table 4. The effects of cover crops, sawdust amendments, and *Phalaris* on the establishment of individual target community species and total graminoid, total forb, and total target community establishment.*

Cover Crop Treatment Sawdust Amendment Species	High-Diversity						Low-Diversity						Absent						
	With			Without			With			Without			With			Without			
	<i>Phalaris</i> Present	<i>Phalaris</i> Absent		<i>Phalaris</i> Present	<i>Phalaris</i> Absent		<i>Phalaris</i> Present	<i>Phalaris</i> Absent		<i>Phalaris</i> Present	<i>Phalaris</i> Absent		<i>Phalaris</i> Present	<i>Phalaris</i> Absent		<i>Phalaris</i> Present	<i>Phalaris</i> Absent		
Bluejoint (<i>Calamagrostis canadensis</i> (Michx.) P. Beauv.)	3 ± 3	7 ± 7	7 ± 4	7 ± 4	0 ± 0	0 ± 0	0 ± 0	0 ± 0	7 ± 4	20 ± 14	20 ± 14	3 ± 3	27 ± 27	40 ± 26	77 ± 43	40 ± 26	27 ± 27	77 ± 43	
American mangrass (<i>Glyceria grandis</i> S. Watts)	50 ± 36	33 ± 20	33 ± 20	33 ± 20	30 ± 14	30 ± 14	47 ± 16	13 ± 10	33 ± 15	100 ± 54	100 ± 54	13 ± 10	93 ± 52	160 ± 51	93 ± 27	160 ± 51	93 ± 52	93 ± 27	
Bottlebrush sedge (<i>Carex hystericina</i> Muhl.)	20 ± 16	17 ± 6	27 ± 20	27 ± 20	7 ± 4	7 ± 4	73 ± 22	93 ± 57	33 ± 18	3 ± 3	3 ± 3	40 ± 17	30 ± 20	40 ± 19	77 ± 47	40 ± 19	30 ± 20	77 ± 47	
Broom sedge (<i>Carex scoparia</i> Schk.)	73 ± 28	170 ± 33	70 ± 39	70 ± 39	97 ± 40	97 ± 40	460 ± 130	310 ± 100	220 ± 45	230 ± 51	230 ± 51	460 ± 91	350 ± 160	360 ± 96	400 ± 120	360 ± 96	350 ± 160	400 ± 120	
Green bulrush (<i>Scirpus atrovirens</i> Willd.)	47 ± 33	63 ± 28	10 ± 10	10 ± 10	17 ± 13	17 ± 13	83 ± 32	67 ± 47	57 ± 23	77 ± 20	77 ± 20	140 ± 87	190 ± 69	63 ± 29	140 ± 43	63 ± 29	190 ± 69	140 ± 43	
Total graminoids	190 ± 86	270 ± 45	150 ± 29	150 ± 29	150 ± 51	150 ± 51	660 ± 160	480 ± 140	350 ± 79	440 ± 100	440 ± 100	660 ± 40	690 ± 170	660 ± 190	780 ± 100	660 ± 190	690 ± 170	780 ± 100	
Allegheny monkeyflower (<i>Mimulus ringens</i> L.)	17 ± 8	27 ± 19	10 ± 4	10 ± 4	7 ± 4	7 ± 4	57 ± 16	50 ± 20	90 ± 40	120 ± 66	120 ± 66	110 ± 53	63 ± 35	70 ± 21	27 ± 14	70 ± 21	63 ± 35	27 ± 14	
Prairie ironweed (<i>Vernonia fasciculata</i> Michx.)	210 ± 56	290 ± 52	190 ± 30	190 ± 30	270 ± 24	270 ± 24	280 ± 81	120 ± 27	360 ± 55	350 ± 93	350 ± 93	490 ± 120	170 ± 42	350 ± 72	170 ± 42	350 ± 72	170 ± 42	170 ± 42	
Virginia mountainmint (<i>Pycnanthemum virginianum</i> L.)	7 ± 4	10 ± 7	7 ± 4	7 ± 4	0 ± 0	0 ± 0	17 ± 6	0 ± 0	7 ± 4	17 ± 9.5	17 ± 9.5	7 ± 4	3.3 ± 3.3	7 ± 4	3 ± 3	7 ± 4	3.3 ± 3.3	3 ± 3	
Great blue lobelia (<i>Lobelia siphilitica</i> L.)	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Spotted joe-pye weed (<i>Eupatorium maculatum</i> L.)	37 ± 33	10 ± 4	17 ± 8.0	17 ± 8.0	10 ± 10	10 ± 10	20 ± 7	13 ± 7	33 ± 11	63 ± 29	63 ± 29	67 ± 23	50 ± 17	33 ± 16	33 ± 7	33 ± 16	50 ± 17	33 ± 7	
Total forbs	270 ± 95	340 ± 49	230 ± 27	230 ± 27	290 ± 30	290 ± 30	380 ± 83	180 ± 37	490 ± 65	550 ± 130	550 ± 130	670 ± 120	290 ± 49	460 ± 79	230 ± 41	460 ± 79	290 ± 49	230 ± 41	
Total target community	460 ± 110	610 ± 52	370 ± 45	370 ± 45	440 ± 53	440 ± 53	1000 ± 220	670 ± 160	840 ± 140	990 ± 210	990 ± 210	1300 ± 150	980 ± 210	1100 ± 220	1000 ± 110	1100 ± 220	980 ± 210	1000 ± 110	

* Values shown are shoots/m² ± SE.

Table 5. Results of analyses of shoot densities (establishment) (A) of individual target community species, total graminoids, total forbs, and total target community, and results of analyses of individual species cover class (growth) (B).*

<i>p</i> Values From Analyses of Shoot Densities (<i>N</i> = 72)								
(A) Model Term	<i>df</i>	<i>Calamagrostis canadensis</i>	<i>Glyceria grandis</i>	<i>Carex scoparia</i>	<i>Scirpus atrovirens</i>	Total Graminoids	Total Forbs	Total Target Community
Basin	1	—	—	—	—	—	0.02	—
Distance from water	2	—	—	—	—	—	—	—
Basin × distance from water	2	—	—	—	—	—	—	—
Elevation	1	—	—	—	—	—	—	—
Cover crops	2	0.03	0.05	<0.0001	0.001	<0.0001	0.06	<0.0001
<i>Phalaris</i>	1	—	—	—	—	—	0.02	—
Sawdust	1	0.003	0.007	—	—	—	—	—
Cover crops × <i>Phalaris</i>	2	—	—	—	—	—	0.003	—
Cover crops × sawdust	2	—	—	—	—	—	0.004	—
<i>Phalaris</i> × sawdust	1	—	—	—	—	—	—	—
Cover crops × <i>Phalaris</i> × sawdust	2	—	—	—	—	—	—	—
Residual	54							
Total	71							

<i>p</i> Values From Analyses of Ordinal Cover Classes (<i>N</i> =72)							
(B) Model Term	<i>df</i>	<i>Carex scoparia</i>	<i>Scirpus atrovirens</i>	<i>Mimulus ringens</i>	<i>Vernonia fasciculata</i>	<i>Pycnanthemum virginianum</i>	<i>Eupatorium maculatum</i>
Basin	1	—	—	—	—	—	—
Distance from water	2	—	—	—	—	—	—
Basin × distance from water	2	—	0.006	0.01	0.004	—	—
Elevation	1	—	0.02	—	—	< 0.0001	—
Cover crops	2	<0.0001	0.005	<0.0001	<0.0001	<0.0001	<0.0001
<i>Phalaris</i>	1	—	0.05	—	—	—	—
Sawdust	1	—	—	0.007	—	0.06	—
Cover crops × <i>Phalaris</i>	2	—	—	0.02	0.007	—	—
Cover crops × sawdust	2	—	—	0.05	0.02	—	0.003
<i>Phalaris</i> × sawdust	1	—	—	0.02	0.002	—	—
Cover crops × <i>Phalaris</i> × sawdust	2	—	—	—	0.05	—	—
Residual	54						
Total	71						

* Basin, distance from water, and basin × distance from water were included in the model as block effects. Individual species densities were rank transformed and total graminoid, total forb, and total target community densities were square root transformed prior to analyses. Only components of the target community having significant whole-model test results are presented. Only significant and marginally significant values are shown. Values in italics are marginally significant ($0.10 > p > 0.05$).

Table 6. The effects of cover crops, sawdust amendments, and *Phalaris* on growth of individual target community species.*

Target Community Species	Cover Crops			Sawdust Amendment		Phalaris	
	High-Diversity (<i>N</i> = 24)	Low-Diversity (<i>N</i> = 24)	Absent (<i>N</i> = 24)	Yes (<i>N</i> = 36)	No (<i>N</i> = 36)	Present (<i>N</i> = 36)	Absent (<i>N</i> = 36)
<i>Calamagrostis canadensis</i>	0 (13)	0 (18)	0 (12)	0 (26)	0 (17)	0 (21)	0 (22)
<i>Glyceria grandis</i>	0 (10)	2 (10)	2 (13)	0 (19)	2 (20)	2 (16)	2 (16)
<i>Carex hystericina</i>	0, 1 (9)	2 (10)	2 (10)	2 (16)	1 (13)	1 (15)	2 (12)
<i>Carex scoparia</i>	2 (15)	2 (14)	3 (15)	2 (19)	2 (17)	0 (20)	2 (16)
<i>Scirpus atrovirens</i>	0 (11)	2 (12)	3 (14)	3 (15)	2 (17)	0, 2 (13)	3 (15)
<i>Mimulus ringens</i>	1 (15)	2 (16)	2 (10)	1 (14)	2 (18)	1 (16)	2 (18)
<i>Vernonia fasciculata</i>	3, 4 (10)	5 (11)	5 (12)	5 (13)	5 (13)	5 (14)	4 (13)
<i>Pycnanthemum virginianum</i>	0 (14)	1 (15)	1 (15)	1 (23)	1 (17)	1 (24)	1 (16)
<i>Lobelia siphilitica</i>	0 (24)	0 (23)	0 (21)	0 (33)	0 (35)	0 (36)	0 (32)
<i>Eupatorium maculatum</i>	0 (12)	2 (10)	2 (10)	1 (18)	0, 2 (12)	1 (13)	2 (12)

* Values recorded are modal cover class (number of plots sampled with that cover class) at the end of the growing season (week 16). The total number of plots sampled are listed on top of each column. If two values are listed, then the data were bimodal. Ordinal cover classes are as follows: 0 = 0%; 1 = less than 1%; 2 = 1–4%; 3 = 5–24%; 4 = 25–49%; 5 = 50–74%; and 6 = 75–100%. Values in bold are significantly different and values in italics are marginally different ($0.10 > p > 0.05$).

further research. Even when *Phalaris* seeds are present at low densities, reducing resources and establishing perennial species does not totally prevent reinvasion, making follow-up *Phalaris* control a necessary aspect of sedge meadow restorations.

Implications for Practice

- When trying to prevent *Phalaris* reinvasions, practitioners should focus efforts on establishing native perennial species quickly, possibly by seeding at high densities and cold stratifying seeds to break dormancy.
- Cover crops are not effective for sedge meadow restorations because they fail to prevent *Phalaris* germination while reducing seedling establishment of desired species.
- Given the logistical difficulties of incorporating sawdust and its limited effectiveness in reducing *Phalaris* seedling establishment, sawdust amendments may be an impractical *Phalaris*-control strategy in sedge meadow restorations. Practitioners who use sawdust should choose sawdust with high C:N ratios because sawdust with low C:N ratios may only reduce N short term.
- Ongoing *Phalaris* control in sedge meadow restorations will be necessary even if *Phalaris* seed densities are low, resource availability is decreased, and native species establish.
- Future restorations that could be affected by invasive species may also benefit from research that increases rates of germination and seedling establishment of desired native species.

Acknowledgments

Funding for this study was provided by the Minnesota Department of Transportation, the Dayton-Wilkie Natural History Fund, a Department of Ecology, Evolution, and Behavior Block Grant (University of Minnesota), the Florence Rothman Fellowship, and a J. E. Weaver Competitive Grant from the Nebraska Chapter of the Nature Conservancy. This research would not have been possible without the help of the following people: Russ Barnsworth, Julia Bohnen, Deren Eaton, Samantha Hensley, Karin Kettenring, Stacey Olszewski, Andy Place, Jon Parsinen, Matt Schuth, Sara Simmers, and Kathleen M. Thompson. Statistical advice was provided by Dennis Cook, Steven J. McKay, and Sanford Weisberg. Throughout the study, Jeannine Cavender-Bares, Robert Jacobson, and Carl Rosen provided technical advice. Suggestions from two anonymous reviewers improved the quality of the manuscript. Lastly, we dedicate this article to the memory of Robert Jacobson.

LITERATURE CITED

- Adams, C. R., and S. M. Galatowitsch. 2005. *Phalaris arundinacea* (reed canary grass): rapid growth and growth pattern in conditions approximating newly restored wetlands. *Ecoscience* **12**:569–573.
- Adams, C. R., and S. M. Galatowitsch. 2006. Increasing the effectiveness of reed canary grass (*Phalaris arundinacea* L.) control in wet meadow restorations. *Restoration Ecology* **14**:441–451.
- Averett, J. M., R. A. Klips, L. E. Nave, S. D. Frey, and P. S. Curtis. 2004. Effects of soil carbon amendments on nitrogen availability and plant growth in an experimental tallgrass prairie restoration. *Restoration Ecology* **12**:568–574.
- Bakker, J. D., and S. D. Wilson. 2004. Using ecological restoration to constrain biological invasion. *Journal of Applied Ecology* **41**:1058–1064.
- Barger N. N., C. M. D'Antonio, T. Ghneim, and E. Cuevas. 2003. Constraints to colonization and growth of the African grass, *Melinis minutiflora*, in Venezuelan savanna. *Plant Ecology* **167**:31–43.
- Baskin, C. C., and J. M. Baskin. 1998. Seeds: ecology, biogeography, and evolution of dormancy and germination. Academic Press, New York.
- Blumenthal, D. M., N. R. Jordan, and M. P. Russell. 2003. Soil carbon addition controls weeds and facilitates prairie restoration. *Ecological Applications* **13**:605–615.
- Bohnen, J. L., and S. M. Galatowitsch. 2005. Spring peeper meadow: revegetation practices in a seasonal wetland restoration in Minnesota. *Ecological Restorations* **23**:172–181.
- Brinson, M. M., and A. I. Malvárez. 2002. Temperate freshwater wetlands: types, status, and threats. *Environmental Conservation* **29**: 115–133.
- Chapuis, J. L., Y. F. Frenot, and M. Lebouvier. 2004. Recovery of native plant communities after eradication of rabbits from subantarctic Kerguelen Islands, and influence of climate change. *Biological Conservation* **117**:167–179.
- Courchamp, F., J. L. Chapuis, and M. Pascal. 2003. Mammal invaders on islands: impact, control, and control impact. *Biological Reviews* **78**: 347–383.
- Davis, M. A., J. P. Grime, and K. Thompson. 2000. Fluctuating resources in plant communities: a general theory of invasibility. *Journal of Ecology* **88**:528–534.
- Dukes, J. S., and H. A. Mooney. 1999. Does global change increase the success of biological invaders? *Trends in Ecology and Evolution* **14**: 135–139.
- Eriksson, O. 2002. Ontogenetic niche shifts and their implications for recruitment in three clonal *Vaccinium* shrubs: *Vaccinium myrtillus*, *Vaccinium vitis-idaea*, and *Vaccinium oxycoccos*. *Canadian Journal of Botany* **80**:635–641.
- Eschen, R., S. R. Mortimer, C. S. Lawson, A. R. Edwards, A. J. Brook, J. M. Igual, K. Hedlund, and U. Schaffner. 2007. Carbon addition alters vegetation composition on ex-arable fields. *Journal of Applied Ecology* **44**:95–104.
- Eschen, R., H. Müller-Schärer, and U. Schaffner. 2006. Soil carbon addition affects plant growth in a species-specific way. *Journal of Applied Ecology* **43**:35–42.
- Galatowitsch, S. M., N. O. Anderson, and P. D. Ascher. 1999a. Invasiveness in wetland plants in temperate North America. *Wetlands* **19**: 733–755.
- Galatowitsch, S. M., and L. A. Biederman. 1998. Vegetation and seed-bank composition of temporarily flooded *Carex* meadows and implications for restoration. *International Journal of Ecology and Environmental Sciences* **24**:253–270.
- Galatowitsch, S. M., R. Budelsky, and L. Yetka. 1999b. Revegetation strategies for northern temperate glacial marshes and meadows. Pages 225–241 in W. Streever, editor. An international perspective on wetland rehabilitation. Kluwer Academic Publishers, Dordrecht, The Netherlands.

- Galatowitsch, S. M., and A. G. van der Valk. 1996. The vegetation of restored and natural prairie wetlands. *Ecological Applications* **6**: 102–112.
- Gleason, H. A., and A. Cronquist. 1991. Manual of vascular plants of northeastern United States and adjacent Canada. 2nd edition. The New York Botanical Garden, Bronx.
- Grabe, D. F. 1970. Tetrazolium testing handbook: for agricultural seeds. Contribution No. 29 to the handbook on seed testing. Association of Official Seed Analysts, Lincoln, Nebraska.
- Green, E. K., and S. M. Galatowitsch. 2002. Effects of *Phalaris arundinacea* and nitrate-N addition on the establishment of wetland plant communities. *Journal of Applied Ecology* **39**:134–144.
- Grubb, P. J. 1977. The maintenance of species-richness in plant communities: the importance of the regeneration niche. *Biological Reviews of the Cambridge Philosophical Society* **52**:107–145.
- Harms, R. S., and R. D. Hiebert. 2006. Vegetation response following invasive tamarisk (*Tamarix* spp.) removal and implications for riparian restoration. *Restoration Ecology* **14**:461–472.
- Hulme, P. E., and E. T. Bremner. 2006. Assessing the impact of *Impatiens glandulifera* on riparian habitats: partitioning diversity components following species removal. *Journal of Applied Ecology* **43**:43–50.
- Iannone, B. V. III. 2007. Evaluation of resource-limiting strategies intended to facilitate sedge meadow restorations by preventing *Phalaris arundinacea* L. invasion. M.Sc. Thesis. University of Minnesota, St. Paul.
- Jacobson, R. L. 2003. Guidelines for restoring & managing native wetland vegetation. Minnesota Department of Transportation and Minnesota Board of Soil and Water Resources (available from <http://www.bwsr.state.mn.us/wetlands/publications/nativewetveg.pdf>) accessed on 30 August 2004.
- Johnstone, I. M. 1986. Plant invasion windows: a time-based classification of invasion potential. *Biological Reviews* **61**:369–394.
- Kettenring, K. M. 2006. Seed ecology of wetland *Carex* spp.—implications for restoration. Ph.D. Dissertation. University of Minnesota, St. Paul.
- Kettenring, K. M., and S. M. Galatowitsch. 2007. Tools for *Carex* revegetation in freshwater wetlands: understanding dormancy loss and germination temperature requirements. *Plant Ecology* **193**:157–169.
- Kettenring, K. M., G. Gardner, and S. M. Galatowitsch. 2006. Effects of light on seed germination of eight wetland *Carex* species. *Annals of Botany* **98**:869–874.
- Lavoie, C., C. Dufresne, and F. Delisle. 2005. The spread of reed canary-grass (*Phalaris arundinacea*) in Québec: a spatio-temporal perspective. *Ecoscience* **12**:366–375.
- Lindig-Cisneros, R., and J. B. Zedler. 2001. Effects of light on seed germination in *Phalaris arundinacea* L. (reed canary grass). *Plant Ecology* **155**:75–78.
- Lindig-Cisneros, R., and J. B. Zedler. 2002a. *Phalaris arundinacea* seedling establishment: effects of canopy complexity in fen, mesocosm, and restoration experiments. *Canadian Journal of Botany* **80**: 617–624.
- Lindig-Cisneros, R., and J. B. Zedler. 2002b. Relationship between canopy complexity and germination microsites for *Phalaris arundinacea* L. *Oecologia* **133**:159–167.
- Morrison, J. A. 2002. Wetland vegetation before and after experimental purple loosestrife removal. *Wetlands* **22**:159–169.
- Neely, R. K., and J. L. Baker. 1989. Nitrogen and phosphorus dynamics and the fate of agricultural runoff. Pages 92–131 in A. van der Valk, editor. Northern prairie wetlands. Iowa State University Press, Ames.
- Ode, D. J., L. L. Tieszen, and J. C. Lerman. 1980. The seasonal contribution of C₃ and C₄ plant species to primary production in a mixed prairie. *Ecology* **61**:1304–1311.
- Ogden, J.A.E., and M. Rejmánek. 2005. Recovery of native plant communities after the control of a dominant invasive plant species, *Foeniculum vulgare*: implications for management. *Biological Conservation* **125**:427–439.
- Perry, L. G., and S. M. Galatowitsch. 2003. A test of two annual cover crops for controlling *Phalaris arundinacea* invasion in restored sedge meadow wetlands. *Restoration Ecology* **11**:297–307.
- Perry, L. G., and S. M. Galatowitsch. 2004. The influence of light availability on competition between *Phalaris arundinacea* and a native wetland sedge. *Plant Ecology* **170**:73–81.
- Perry, L. G., S. M. Galatowitsch, and C. J. Rosen. 2004. Competitive control of invasive vegetation: a native wetland sedge suppresses *Phalaris arundinacea* in carbon-enriched soil. *Journal of Applied Ecology* **41**:151–162.
- R Development Core Team. 2008. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria (available from <http://www.R-project.org>).
- Schupp, E. W. 1995. Seed-seedling conflicts, habitat choice, and patterns of recruitment. *American Journal of Botany* **82**:399–409.
- Schütz, W., and G. Rave. 1999. The effect of cold stratification and light on the seed germination of temperate sedges (*Carex*) from various habitats and implications for regenerative strategies. *Plant Ecology* **144**:215–230.
- Seabloom, E. W., W. S. Harpole, O. J. Reichman, and D. Tilman. 2003. Invasion, competitive dominance, and resource use by exotic and native Californian grassland species. *Proceedings of the National Academy of Sciences of the United States of America* **100**:1384–1389.
- Sheley, R. L., and M. L. Half. 2006. Enhancing native forb establishment and persistence using a rich seed mixture. *Restoration Ecology* **14**: 627–635.
- Tilman, D. 1982. Resource competition and community structure. Monographs of population biology. Princeton University Press, Princeton, New Jersey.
- Tilman, E. A., D. Tilman, M. J. Crawley, and A. E. Johnston. 1999. Biological control via nutrient competition: potassium limitation of dandelions. *Ecological Applications* **9**:103–111.
- Wetzel, P. R., and A. G. van der Valk. 1998. Effects of nutrients and soil moisture on competition between *Carex stricta*, *Phalaris arundinacea*, and *Typha latifolia*. *Plant Ecology* **138**:179–190.
- Zavaleta E. S., R. J. Hobbs, and H. A. Mooney. 2001. Viewing invasive species removal in a whole-ecosystem context. *Trends in Ecology and Evolution* **16**:454–459.
- Zink, T. A., and M. F. Allen. 1998. The effects of organic amendments on the restoration of a disturbed coastal sage scrub habitat. *Restoration Ecology* **6**:52–58.