Biol Invasions (2010) 12:781–793
DOI 10.1007/s10530-009-9481-9

ORIGINAL PAPER

Restoring restoration: removal of the invasive plant *Microstegium vimineum* from a North Carolina wetland

Julie E. DeMeester · Daniel deB. Richter

Received: 12 December 2008 / Accepted: 26 May 2009 / Published online: 12 June 2009

Abstract Restoration sites are vulnerable to plant invasions due to habitat and resource alteration. We conducted an invasive plant-removal study at a wetland restoration in the North Carolina Piedmont, a site dominated by the non-native invasive, *Microstegium vimineum*. Paired plots (*M. vimineum* hand-weeded and unweeded) were established and maintained to monitor response of plant species richness and diversity. Plots increased from 4 to 15 species m^{-2} after three growing seasons of *M. vimineum* removal and 90% of the newly establishing species were native. Weeding ceased in the fourth growing season and *M. vimineum* rapidly re-invaded. Formerly weeded plots increased to 59% (±11% SE) *M. vimineum* cover, 25 of 51 plant species disappeared from the plots, and species richness decreased to an average of <8 species m^{-2}. Our results show that we can quickly establish an abundant, diverse community with invasive removal, but that persistent effort is required to monitor and maintain the long-term viability of this community.

J. E. DeMeester · D. deB. Richter (✉)
Duke University, P.O. Box 90328, Durham, NC 27705, USA
e-mail: drichter@duke.edu

J. E. DeMeester
e-mail: Jed16@duke.edu

Keywords Ecosystem restoration · *Microstegium vimineum* · Invasion · Diversity · Wetland

Introduction

Wetland restorations offer a special opportunity for ecologists to recreate proper wetland hydrology, enhance biodiversity and promote nutrient cycling of elements in degraded ecosystems. The United States has lost nearly 50 million ha of wetlands and stream riparian corridors from pre-settlement time to 1980 (Dahl 1990; Mitsch and Gosselink 2000). Since a “no net loss” policy was introduced into the Clean Water Act at the National Wetlands Policy Forum in 1988), wetland and stream restorations have become important tools in mitigating the loss of natural wetland functions. Yet the disturbance associated with restoration construction provides opportunities for invasive plants to establish (D’Antonio and Meyerson 2002), and invasive species are now widely recognized to be a factor interfering with restoration ecosystem success (Zedler and Callaway 1999). In a study of forty-one restored sites 3 years or older, all sites contained a higher abundance of invasive species than native species, and invasives formed dense monocultures within the restored systems (Mulhouse and Galatowitsch 2003). While natural wetlands are also hotspots for invasives (Zedler and

Kercher 2004), the goal of restoration is to improve degraded ecosystems and create well-functioning communities; monocultures of invasive plants detract from this goal.

Invasive plant species have many unknown, yet potentially long-lasting ecological effects as they spread into new habitats (D'Antonio and Vitousek 1992; Mack et al. 2000). Invasive species alter ecosystem functions (D'Antonio and Vitousek 1992; Ehrenfeld 2003; Hooper and Vitousek 1998; Zedler and Kercher 2004), which lends the potential to modify wetlands' beneficial effects on water quality, nutrient retention, biogeochemical cycling of elements, decomposition of organic matter, community and wildlife habitat, and flood control (Mitsch and Gosselink 2000). Hence, it is unpredictable how wetland restoration sites will function when they are heavily dominated by invasive species.

Simultaneously, little is known about the ability of an invaded restoration site to rebound if the invasives are removed from the system. Predicting the new plant community is difficult because soil seed banks have been altered by both the disturbance of restoration activities and the invasive species. Additionally, riparian wetlands receive plant propagules from multiple sources including seeds from nearby terrestrial plants as well as stream-borne seeds (Zedler and Kercher 2004). A major concern is that when a dominant invasive plant is removed, another dominant invasive plant may take its place, wasting time and monetary resources (Hobbs and Humphries 1995; Mack et al. 2000). It is also feasible that the same invasive plant to first dominate the restoration site could return in the absence of persistent yearly removal. While it is long thought that establishing a diverse native community will minimize invasive establishment (Elton 1958; Kennedy et al. 2002; Tilman 1997), it is unclear what level and length of effort would be required to do this in a restoration setting.

The majority of wetland loss in the conterminous United States has occurred in the Southeast (Hefner et al. 1994), and hence this region has many active restoration projects (Dahl 2006). *Microstegium vimineum* is a particularly aggressive non-native plant that thrives in riparian and wetland habitats, and spans the Southeast from Connecticut south to Florida, and west to Texas (USDA 2005). It is an exotic C_4 grass from Asia that was first reported in Knoxville, TN in 1919 (Fairbrothers and Gray 1972). *M. vimineum* rapidly disperses by water and animals and invades floodplains, stream banks, adjacent slopes, roadsides, and other disturbed locations (Redman 1995). It is an annual plant that propagates both by seed and vegetative runners, grows quickly, and fruits prolifically within a single season with seeds remaining viable in the soil for 3–5 years (Barden 1987; Gibson et al. 2002). *M. vimineum* is slow to invade undisturbed vegetation, but can outcompete native vegetation and create nearly monospecific stands in disturbed locations within 3 years (Barden 1987). The species is highly plastic and can survive and be successful in wet, dry, sunny and shady locations (Claridge and Franklin 2002; Cole and Weltzin 2004). With its abundant growth, high plasticity and high reproductive potential, *M. vimineum* can be treated as a model species to examine invasion in restoration sites of Southeastern wetlands.

Specific objectives

This research evaluated how the plant community composition of a restored riparian wetland in North Carolina, which had been dominated by *M. vimineum* since the completion of restoration (more than 3 years), rebounded once *M. vimineum* was removed. Invasive removal was conducted for 3 years to determine species recruitment, abundance, plant diversity, and plant type (i.e. other invasives, trees, etc.) with the hypothesis that plant diversity would significantly increase when *M. vimineum* was removed. Subsequently, removal ceased for the fourth growing season to determine the robustness of the native communities from re-invasion of *M. vimineum*. While it was expected that *M. vimineum* would return to the plots, we hypothesized that 3 years of plant community development would allow enough establishment and growth for the species to resist dominance by *M. vimineum*.

Methods

Site description

The Yates Millpond restoration is located within the Southern Piedmont in Eastern North America, in Raleigh, North Carolina USA. Prior to restoration, the Yates Millpond tributary stream had become heavily incised due to human development in the watershed. Increased impervious surfaces created faster water flow rates that cut through the stream channel and stream banks. The stream measured two and a half meters deep, over three and a half meters wide, and lacked sinuosity. The deeply incised channel affected the surrounding riparian wetlands by lowering the groundwater table of the riparian zone, as well as eliminating stream bank overflow during high rain events. Using a nearby local stream as a reference, the goal of the restoration was to reconnect the stream to the surrounding riparian wetlands by re-contouring and raising the Yates Millpond streambed. The expected results were a rise in the groundwater table, as well as periodic stream bank overflow events.

Over 1,200 linear meters of stream were restored in two phases. Phase 1 was completed in 2000, re-contouring over 300 m of the stream. Phase 2 was completed in 2002 and created over 900 m of an entirely new channel for the stream, with shallow banks less than a meter deep and high sinuosity. The old stream channel was partially refilled, with several large trenches left to create small ponds.

Heavy machinery was used for the reconstruction of the stream, removing the floodplain vegetation in order to complete the stream design (Fig. 1). As soon as the stream was re-routed, the restoration practitioners planted live stakes of native tree seedlings in order to stimulate a forest riparian buffer. *Lolium perenne*, an introduced perennial grass, was seeded for ground cover. As desired, the water table of the floodplain increased by nearly 2 m, restoring both the stream and the adjacent floodplain wetlands.

The *L. perenne* ground cover did not persist and riparian areas at Yates Millpond became heavily invaded by the exotic invasive *M. vimineum* in the first growing season after restoration was complete. The land manager reports that there had been some *M. vimineum* prior to restoration, but that it was not prolific. By the 2004 growing season, 2 years after restoration, *M. vimineum* accounted for greater than 80 percent of the herbaceous floodplain ground cover vegetation (Fig. 2).

Experimental design

A *M. vimineum* removal experiment was initiated in June 2005 in plots scattered throughout the floodplain. After restoration, elevated water tables within the floodplain stressed and killed numerous overstory trees, creating several acres of open light conditions (light levels above 1,200 μmol/m^2 s at peak sun). Six pairs of side-by-side 1 m^2 plots (12 total) were established in these open light areas of the floodplain. The paired plots were at least 3 m apart. One plot of each of the six pairs was designated as a *M. vimineum* removal plot, hereafter referred to as "weeded plots," while the adjacent plot was designated as an unweeded *M. vimineum* control plot, hereafter referred to as "*M. vimineum* plots." Statistical analysis of species cover for the paired plots showed they were not significantly different from

Fig. 1 Restoration construction disturbance at Yates Millpond in Raleigh, NC

Fig. 2 Yates Millpond post-restoration, dominated by the invasive *M. vimineum*

each other prior to treatment. *M. vimineum* cover of these plots ranged from 55 to 100 percent. In 2006, all 1 m^2 plots were expanded in area to 2.25 m^2, with the extra plot area providing a buffer to help minimize edge effects. This required moving the *M. vimineum* plots 0.50 m from the original 2005 location. There was no statistical difference in the amount of *M. vimineum* cover in the altered locations.

Microstegium vimineum removal began on June 15, 2005 and lasted through October of 2007. *M. vimineum* was continuously hand-pulled (at least bi-weekly) from all the plots designated as weeded plots. *M. vimineum* has a shallow root structure and can be weeded with minimal soil disturbance. Any vegetation that was not *M. vimineum* was left in the plot. From 2005 through 2007, eight plant surveys were conducted by estimating percent cover of all established vegetation rooted in the 12 plots. Four of these surveys were conducted monthly in 2005 from June to September. Two surveys each were conducted in 2006 and 2007 during the early and late growing season. Treatment ceased at the end of the growing season in 2007 and *M. vimineum* was allowed to re-invade the plots. One additional plant survey was completed at the end of the growing season in 2008 to track the robustness of the established community to *M. vimineum* re-invasion.

Data analysis methods

All plant surveys were analyzed for differences in species richness, evenness, and Shannon diversity (Begon et al. 1986) between the weeded and *M. vimineum* plots using a paired *t*-test for significance. Rank-abundance charts were created using the last plant survey of the weeding treatment (9/23/07). The fastest-spreading species were identified by comparing the species percent cover at time zero to the species percent cover at end of the weeding treatment (June 2005–Sept 2007). Additionally, the change in species cover for the fastest-spreading species post-treatment was analyzed by comparing the species cover at the end of the weeding treatment to species cover 1 year post-treatment (Sept 2007–Oct 2008). Tree seedling establishment was analyzed using presence–absence data for each species. Species data were obtained from the USDA Plants Database (USDA 2008) to determine native ranges and growth form. Plant species were determined to be “weeds” (plants that reproduce and grow aggressively) by combining information from the USDA Plants Database (USDA 2008) and the Weed Science Society of America (WSSA 2008). Community attribute data for *M. vimineum* and weeded plots were analyzed using species counts for each category.

A Non-metric Multidimensional Scaling (NMS) ordination was created in PC-ORD for Windows, Version 4.03 (McCune and Mefford 1999) to show the relationships among plots based on species composition. This ordination uses an iterative technique based on ranked distances between sites and makes no assumptions of normality (Kruskal 1964; Mather 1976). A stress value is computed to evaluate the departure in monotonicity between the distances in the original, multidimensional space and the distance in the reduced dimensional space (McCune and Grace 2002); the stress value informs the appropriate number of axes. All six plant surveys were used in creating a species matrix; each plot was assigned its treatment and a date in the matrix. Rare plants were discarded from the matrix by only including plants that were greater than 1% of either the *M. vimineum* plots or the weeded plots during the last plant survey of the treatment period (Sept 2007); there were a total of 36 plants in the data matrix. A second matrix was created to assign each plot to a group for future succession vectors.

An initial NMS run was performed to determine the appropriate number of axis (Table 1). A scree plot of stress versus iteration showed that two axes was the best solution; there was very little reduction in

Table 1 NMS criterion for the initial run in PC Ord

NMS criterion	Initial NMS run
Distance measure	Sorensen
No. of axis	6
Step down in dimensionality	Yes
Runs with real data	50
Stability criterion	0.0005
Iterations to evaluate stability	10
Maximum iterations	200
Seed integer	41
Monte Carlo runs	20

stress by having more than a two-axis solution. A final solution was run with the same criterion as the initial run (Table 1), yet with no step-down in dimensionality and only two axes.

Succession vectors connected the plots through time. First, a Mantel test was used to compare *M. vimineum* plots to weeded plots at each time point. The Mantel test evaluates the correlation between distance matrixes, and compares this correlation to randomized permutations (Legendre and Legendre 1998). In addition to a *P* value, the Mantel test will yield a *R* score of between −1 and 1; a value of 1 means matrices are completely different and a value of 0 means matrices are exactly the same. Negative *R* values are rare. For this Mantel analysis, *M. vimineum* plots were compared to the weeded plots using the Sorensen distance dissimilarity matrix on species composition.

Next, a trajectory analysis was conducted to see if plots were moving in a similar direction in species space by measuring each succession vector for distance and angle of direction. For each time step, vectors were translated to a common origin. Vector movement distance, representing the length of each vector, was compared between *M. vimineum* and weeded plots using a Mantel's test for significance (McCune and Grace 2002); Euclidean distance was used to create the dissimilarity matrices. Vector angles were compared by standardizing the vectors to a common length and performing a Mantel's test between *M. vimineum* and weeded plots using Euclidean distance to create the data matrices (McCune and Grace 2002).

Results

Plant recruitment during weeding treatment (June 2005–October 2007)

Removing *M. vimineum* caused a dramatic change in species composition (Fig. 3). Within 1 month, species richness was significantly higher in the weeded plots (Fig. 4). There was a steep increase in the average number of species for weeded plots during the first year, increasing from an average of 4 to 10 species m^{-2} over the course of a growing season. At the end of the second year, there was an average of 12 species m^{-2} compared to 4 species m^{-2} in the *M. vimineum* plots. By the third year, the weeded plots averaged 15 species m^{-2}, while the

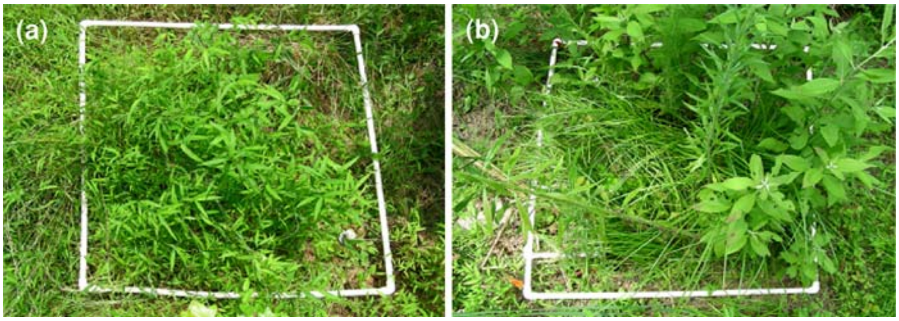

Fig. 3 Side by side quadrats of the *M. vimineum* removal experiment at Yates Millpond in Raleigh, NC. **a** The plant community over-run by the non-native invasive *M. vimineum*. **b** The diverse natural community that establishes when *M. vimineum* is removed

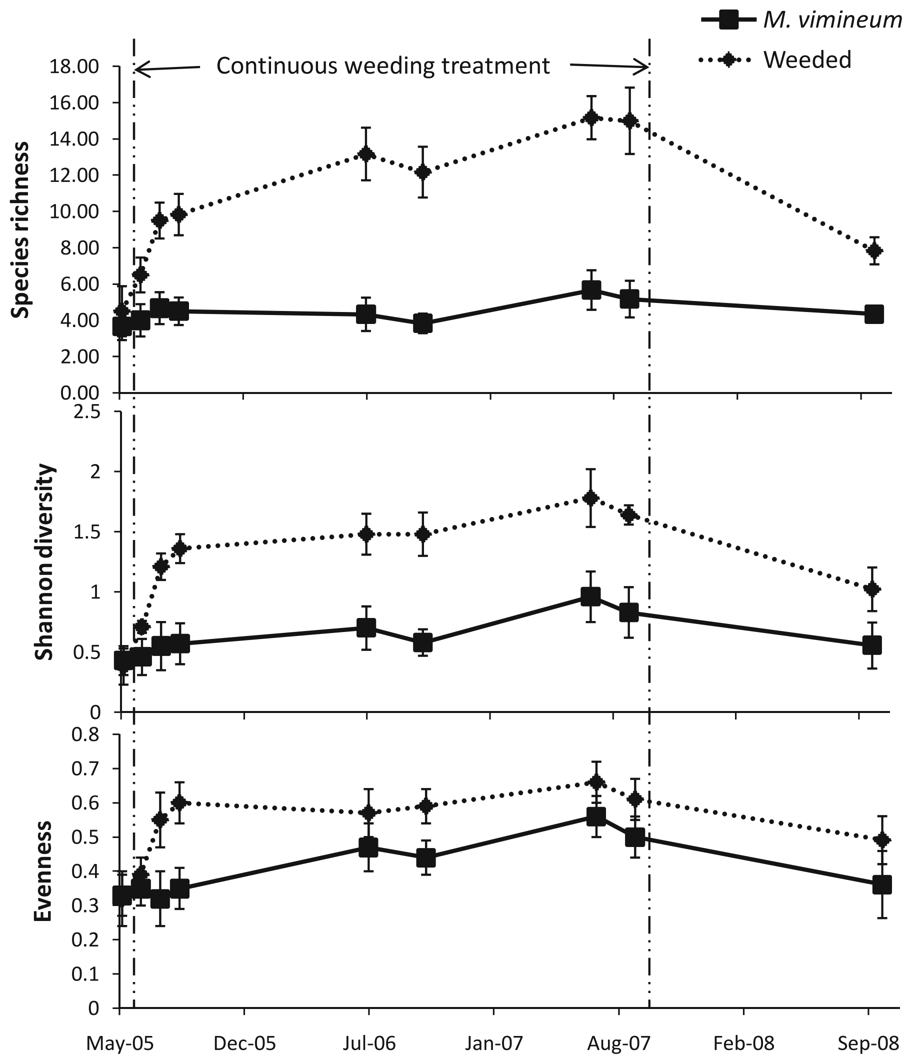

Fig. 4 Species richness, Shannon diversity and evenness for *M. vimineum* and weeded plots for three seasons of weeding treatment and one season post-treatment. *Error bars* are standard error. An evenness score of 1 means complete evenness, 0 means complete unevenness

M. vimineum plots averaged a little over 4 species m^{-2} (Fig. 4).

Shannon diversity and evenness followed a similar pattern to species richness (Fig. 4). There was a significant difference between weeded and unweeded plots after 2 months of *M. vimineum* removal. By the end of the first growing season the weeded plots had a Shannon diversity score that was 139% higher than the *M. vimineum* plots and an evenness score that was 71% higher (Fig. 4). The weeded plots maintained a significantly higher Shannon diversity and evenness score for the duration of the second and third years of weeding (2006 and 2007), being at least 98% higher in Shannon diversity and 22% higher in evenness at the end of each growing season (Fig. 4). To target the specific impacts of *M. vimineum* on the resident plant community, *M. vimineum* percent cover was removed from the not-weeded plot calculations and an even greater discrepancy was found with the weeded plots for species richness, Shannon diversity and evenness ("Appendix").

Rank-abundance plots (Fig. 5) also illustrate effects of *M. vimineum* on species abundance. In the *M. vimineum* plots, 10 of the 19 species (including *M. vimineum*) each represented more than one percent of the total abundance, with *M. vimineum* clearly the dominant plant (Fig. 5a). The weeded plots had 16 of 51 species that each accounted for greater than one percent of the total abundance and these top 16 were more evenly abundant than the *M.*

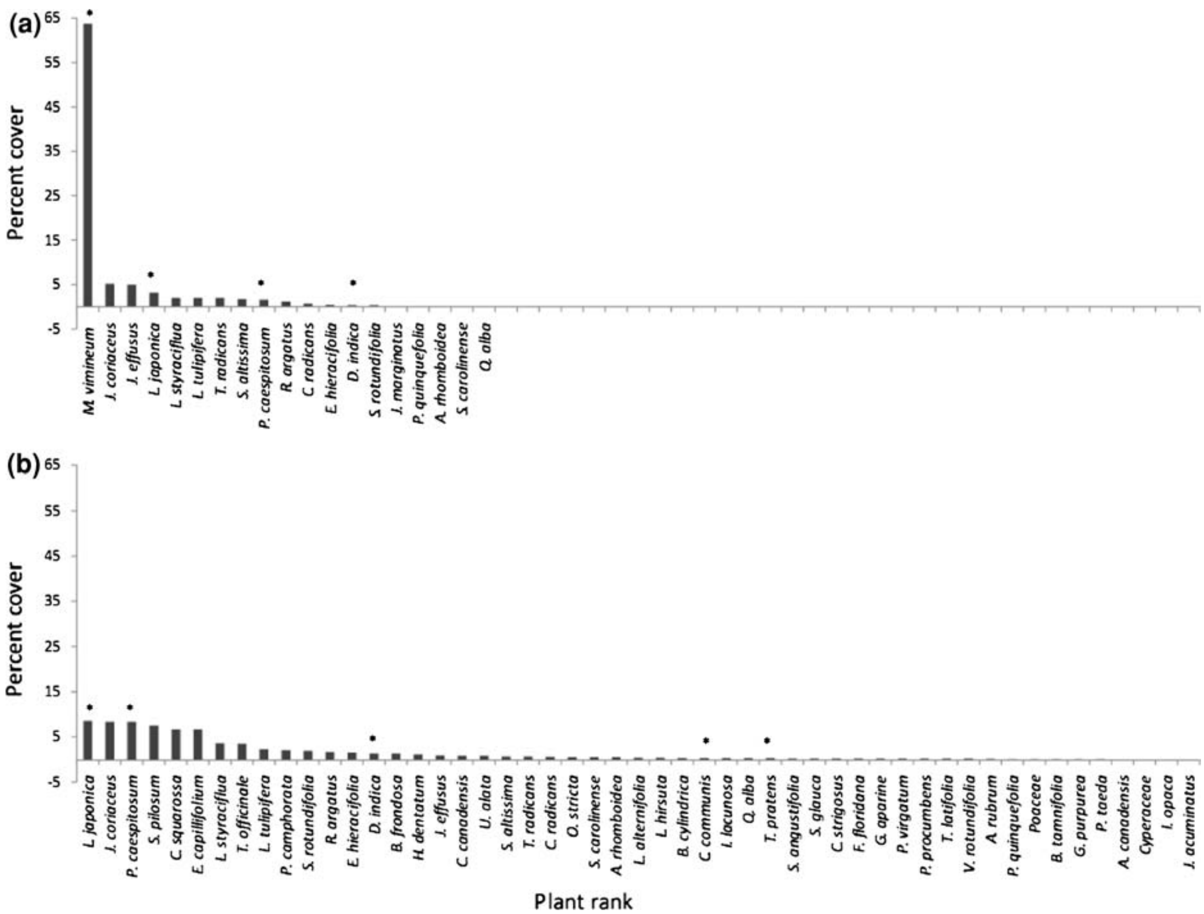

Fig. 5 Plant rank versus average percent cover for (**a**) *M. vimineum* plots and (**b**) weeded plots. * Indicates a non-native species

vimineum plots (Fig. 5b). Yet, the weeded plots contained numerous species that were rare in abundance as species were newly recruiting into the plots.

During the 3 year weeding treatment, invasives (non-*M. vimineum*) did not come to dominate the treatment plots. Twelve of the top 15 most rapidly spreading species were indigenous to central North Carolina (Table 2). There were three fast-spreading non-native species. Only one of these three, *Lonicera japonica*, is considered a non-native invasive. *L. japonica* was the second fastest spreading species over the three season treatment. Yet, 90% of all 51 species that colonized the weeded plots were native species (Table 3). By the end of the 3 year treatment, bare ground covered less than a quarter of the plots, non-native plants covered roughly a quarter of the plots, and natives covered half of the plots (Fig. 6).

The species recruitment into the weeded plots during treatment was roughly one-fourth annuals, and the rest perennials (Table 3). Additionally, there was a diversity of forbs, graminoids, trees seedlings, and vines (Table 3). Hence, the establishing vegetation had structurally diverse canopy architecture. Even still, the majority of plants (82%) that established in the weeded plots were weedy species (Table 3). Overall, weeded plots had a total of 51 species at the end of the treatment versus the *M. vimineum* controls which had 19 (Table 3). This species richness is in spite of the fact that the weeded plots had an average of 20 percent bare ground per plot, versus *M. vimineum* plots having an average of nine percent. There were 34 species in the weeded plots that were never found in the *M. vimineum* plots; these species represented a wide variety of growth forms and plant types (Table 3). Additionally, new tree seedlings established in all weeded plots while new tree seedlings rarely recruited in *M. vimineum* plots (Table 4).

Table 2 Fastest spreading species, increasing at least 1% in plant cover of all the weeded plots from June 2005 (time zero) to October 2007

Rank	Species	% Increase by the end of treatment	% Change 1 year post treatment
1	*Polygonum caespitosum var. longisetum**	8.17	−7.92
2	*Lonicera japonica***	7.67	−3.17
3	*Symphyotrichium pilosum*	7.50	−5.83
4	*Juncus coriaceus*	7.17	−0.83
5	*Carex squarossa*	6.67	−4.17
6	*Eupatorium capillifolium*	6.58	−5.83
7	*Taraxacum officinale*	3.50	−3.50
8	*Liquidambar styraciflua*	2.78	0.05
9	*Pluchea camphorata*	2.00	−2.00
10	*Liriodendron tulipifera*	1.80	−0.22
11	*Rubus argatus*	1.67	0.50
12	*Erichtites hieracifolia*	1.43	−1.52
13	*Bidens frondosa*	1.33	−1.00
14	*Duchesnea indica**	1.18	−1.27
15	*Hypericum dentatum*	1.17	−1.17

The same species and their change 1 year post treatment

* A non-native species

** A non-native invasive species

Table 3 Community attributes totaled across all of the weeded and *M. vimineum* plots at the end of the weeding treatment (September 2007) and again 1 year post treatment (October 2008)

	September 2007 (End of treatment)			October 2008 (1 year post treatment)		
	M.vimineum plots	Weeded plots	Spp unique to weeded plots	*M.vimineum* plots	Weeded plots	Spp lost from weeded plots
Total spp	19	51	34	13	25	27
Native	15 (79)	46 (90)	32	10 (77)	20 (80)	25
Non-native	4 (21)	5 (10)	2	3 (23)	5 (20)	2
Annual	4 (21)	13 (25)	10	4 (31)	5 (20)	9
Biennial	0 (0)	1 (2)	1	0 (0)	0 (0)	1
Perennial	15 (79)	37 (73)	23	9 (69)	20 (80)	17
Forb	7 (37)	26 (51)	19	3 (23)	9 (36)	17
Graminoid	4 (21)	8 (16)	6	3 (23)	4 (16)	5
Subshrub	1 (5)	1 (2)	0	1 (8)	1 (4)	0
Tree	3 (16)	8 (16)	5	3 (23)	6 (24)	2
Vine	4 (21)	8 (16)	4	3 (23)	5 (20)	3
Weedy	17 (89)	42 (82)	26	12 (92)	23 (92)	22
Not weedy	2 (11)	9 (18)	8	1 (8)	2 (8)	5

The first number is a count; the second number in parenthesis is the percent of the count total. Each dotted line category represents the total count/100 percent of the community

Fig. 6 Average non-native, native and bare ground abundance across weeded plots. Standard error is less than 10% for non-native plots, less than 7% for native plots and less than 10% for bare ground

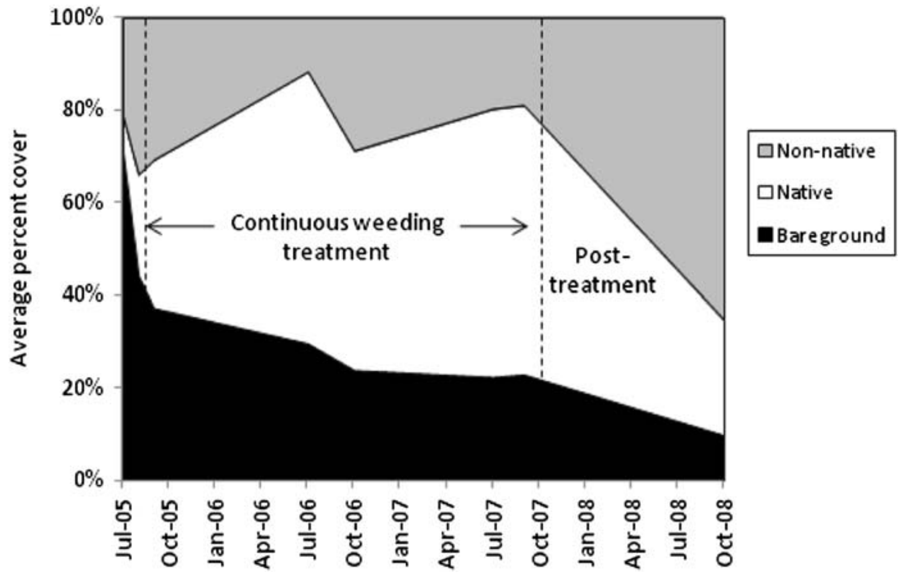

Table 4 Change in presence/absence of tree seedlings in plots during the weeding treatment from July 2005 to September 2007

Tree seedling	*M. vimineum* plots	Weeded plots
Acer rubrum	0	2
Baccharis halimifolia	0	1
Ilex opaca	0	1
Liquidambar styraciflua	−1	1
Liriodendron tulipifera	0	3
Pinus taeda	0	2
Quercas alba	1	1
Total	0	11

For example, *Acer rubrum* was in 1 weeded plot at the start of the treatment, and three weeded plots at the end of the treatment—this species colonized 2 additional weeded plots. A negative value means tree species loss from plots

Plant recruitment post-treatment (October 2008)

In just 1 year following the 3 years of weeding, *M. vimineum* rapidly dominated all plots. *M. vimineum* percent cover averaged 59% (±11% standard error) in the weeded plots and 80% (±8% standard error) in the *M. vimineum* plots. The previously species-rich weeded plots decreased from an average species richness of 14 species m^{-2} to just over 7 species m^{-2} (Fig. 4). As with species richness, diversity and evenness declined as soon as the weeding treatment ceased, and *M. vimineum* was allowed to re-colonize the plots (Fig. 4).

The majority of the fastest spreading species in the weeded plots during the weeding treatment either significantly declined in abundance or disappeared altogether after weeding ended (Table 2). The weeded plots decreased from 51 species, to 25 species (Table 3). Twenty-seven species completely disappeared from the weeded plots in just 1 year's time of not weeding (Table 3).

NMS succession analysis

The NMS succession analysis visually displays how the plots moved in species-space (Fig. 7). The ordination was statistically significant, with the Monte Carlo *P* value of 0.0476, a stress of 11.97, an instability of 0.0003 and 62 iterations for the final solution. Axis 1 represented 0.60 of the variance and axis 2 represented 0.33 of the variance for a total r^2 of 0.93.

All plots were not significantly different from each other before weeding began in June 2005 (Table 5; Fig. 7). The weeded plots moved dramatically away from the *M. vimineum* plots after just one season of weeding (Table 5; Fig. 7a). Weeded plots remained significantly different from *M. vimineum* plots throughout the subsequent 2 years of weeding (Table 5). Yet, Mantel's *R* values indicated that dissimilarity decreased during the weeding period (Table 5). Although remaining significantly different, the weeded plots and *M. vimineum* plots moved

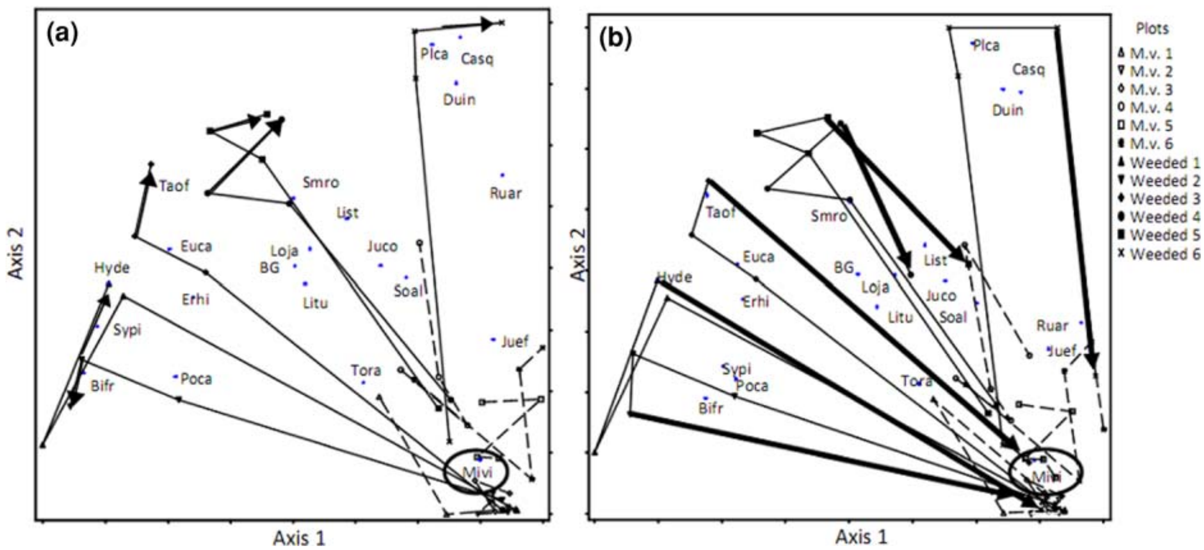

Fig. 7 **a** NMS ordination of plots in species space through time, shown with succession vectors. Points represent pre-treatment (June 2005), Sept 2005, Oct 2006 and Sept 2007. *Dotted lines* are *M. vimineum* plots; *solid lines* are weeded plots. *M. vimineum* is circled in the lower right corner. **b** The same NMS, with 1 year post-treatment data added (Oct 2008) with *bolded arrows*

Table 5 Mantel's statistics comparing *M. vimineum* plots to weeded plots from the NMS scores

Time	Mantel's *R*	*P* value
Jun 2005	−0.05	0.68
Sep 2005	0.85	0.00
Oct 2006	0.75	0.00
Sep 2007	0.61	0.00
Oct 2008	0.01	0.87

closer together in species space; especially in year three, 2007, a year with protracted drought. A year after treatment ended, the *M. vimineum* plots and weeded plots were no longer different from each other in species space (Table 5; Fig. 7b).

Comparing each time-step vector to determine if plots moved through a similar succession pattern, the weeded plots moved in a dramatically different distance and direction compared to the *M. vimineum* plots in the first year (Table 6). The weeded plots and the *M. vimineum* plots did not move in a significantly different distance or direction from each other during the second and third years (Table 6); plots moved in many different directions, yielding no significant differences between the groups. In the last year, the weeded plots moved a significantly greater distance than the *M. vimineum* plots as they lost species and reverted back in species space to become similar in composition to the *M. vimineum* plots (Table 6).

Discussion

The results of this experiment have positive and negative findings for floodplain restoration. First, with removal of *M. vimineum*, a diverse set of native plants were able to rapidly establish. This implies that the seed bank of a previously degraded floodplain (pre-restoration), which was both disturbed with heavy machinery during restoration construction as well as dominated by an invasive species for several years, still has the ability to recruit desirable native plants. While the vegetation in our six weeded plots moved in random successional directions after the first year (Fig. 7a; Table 6), this is likely an artifact of the small plot size. Importantly, trees seedlings increased in establishment when the invasive was removed; this pushes forward the natural succession of the restoration site.

Second, when *M. vimineum* was removed, it was not simply replaced by a monoculture of other invasives. While another invasive established in the

Table 6 Trajectory analysis of vector distance and angle/direction

Time vector	Average vector distance (cm)			Average vector angle (degrees)		
	Weeded	*M. vimineum*	Mantel *P* value	Weeded	*M. vimineum*	Mantel *P* value
June 2005–Sept 2005	12.17 (±1.01)	1.77 (±0.75)	0.00*	138 (±13)	323 (±14)	0.00*
Sept 2005–Oct 2006	3.25 (±0.66)	1.92 (±0.51)	0.63	178 (±28)	148 (±26)	0.65
Oct 2006–Sept 2007	3.42 (±0.70)	2.25 (±0.81)	0.70	37 (±25)	104 (±23)	0.91
Sept 2007–Oct 2008	11.50 (±1.65)	2.50 (±0.81)	0.00*	318 (±13)	306 (±20)	0.38

Asterisk (*) indicates a significant difference between weeded and *M. vimineum* plots

plots, *L. japonica*, it accounted for less than 10 percent of the plot cover after 3 years and altogether non-native species accounted for only a quarter of the plot cover (Figs. 5, 6). The long-term growth of *L. japonica* is unknown, but after three growing seasons in our site, we did not find that another invasive species dominated when an established invasive species was removed.

Still, there are harsh lessons from this experiment. First, we can confirm that *M. vimineum* is strongly invasive in its habitats. A species rich, diverse community of native plants had established after three growing seasons of *M. vimineum* removal. Each year required less and less weeding, as the native vegetation developed. Yet, just one growing season after weeding ceased, *M. vimineum* had heavily re-colonized all formerly weeded plots, and greatly reduced species richness and diversity. We expected *M. vimineum* to re-establish, especially due to the small scale of our treatment plots. Yet, we hypothesized that the diverse community would be more resistant to *M. vimineum* dominance because the diverse plots had several years for the vegetation to establish and grow, and *M. vimineum* was reported as less adept at dominating intact vegetation (Barden 1987). Contrary to our hypothesis, the diverse community was not robust against invasive species dominance. *M. vimineum* was clearly superior in capitalizing resources and suppressing other vegetation. Similar to other studies (Oswalt et al. 2007), the reduction in trees species post-treatment showed evidence that this plant retards tree establishment and succession, heavily impacting the restoration site.

For years, wetland restoration scientists have debated the methods of "self-design" versus "designer" approaches to establishing vegetation in restoration sites. The "self-design" approach allows vegetation to recruit on its own from nearby communities, and saves money and effort by minimizing planting (Mitsch and Wilson 1996; Mitsch et al. 1998). The "designer" approach promotes planting specific species in the restoration site in order to obtain the desired vegetation (Seabloom and van der Valk 2003; Van der Valk 1998). Even with planting native species, invasives have the ability to dominate in restoration sites (Cole 1999). Our research reiterates that neither approach is sufficient enough to create a diverse community of plants if an invasive species is establishing in the restoration site.

We want to emphasize the importance of site selection in the restoration process. Sites which lack invasive species, and with an absence of nearby invasive sources, should be prioritized more highly than sites with invasions already prominent. We recognize that presence of invasives is but one criterion for restoring sites, but it might be made a higher priority than it is today. Another recommendation that springs from this research is to plan for years of invasive species management and control post-restoration. Our data show that the restoration site quickly rebounded with diverse, native plants once the invasive was removed. Yet, the diverse community can disappear without persistent yearly upkeep. Hence, invasive control should become an anticipated cost and component of the long-term restoration plan. While this will increase the cost of restoration, it is critical for creating healthy, diverse ecosystems.

Acknowledgments We would like to give a special thank you to Dr. Mengchi Ho for extensive help with plant surveys and plant identification. Thanks to Karen Hall and Barbara Doll for use of the Yates Millpond site, and to Dr. Dean Urban and Dr. Nicolette Cagle for help with the NMS ordination. This research was supported by funds from the Budweiser Conservation Fellowship, the Society of Wetland Scientists Student Grants, and the Graduate School of Duke University. We appreciate the comments of two anonymous reviewers.

Appendix

See Table 7.

Table 7 Targeted impacts of *M. vimineum*; the average difference between the weeded plots and the *M. vimineum* plots when *M. vimineum* was removed from the not weeded statistics

Date	Species richness	Shannon diversity	Evenness
6/1/2005 pre-weeding	1.83	0.14	0.14
7/1/2005	3.50	0.45	0.17
8/1/2005	5.83	0.83	0.30
9/1/2005	6.33	0.94	0.31
7/1/2006	9.84	1.04	0.29
10/1/2006	9.34	1.09	0.29
7/1/2007	10.50	1.07	0.17
9/1/2007	10.83	1.05	0.24
10/5/2008 post-weeding	3.50	0.37	0.07

For example, by 9/1/2007 species richness would increase by an average of 11 species per m^2, Shannon diversity would increase by 1.05 and evenness would increase 0.24 if *M. vimineum* were not in the plots

References

Barden LS (1987) Invasion of *Microstegium vimineum* (Poaceae), an exotic, annual, shade-tolerant, C-4 grass, into a North-Carolina floodplain. Am Midl Nat 118:40–45. doi:10.2307/2425626

Begon M, Harper JL, Townsend CR (1986) Ecology, individuals, populations and communities. Sinauer Associates, Inc., Sunderland

Claridge R, Franklin S (2002) Compensation and plasticity in an invasive plant species. Biol Invasions 4:339–347. doi:10.1023/A:1023671006342

Cole CA (1999) Ecological theory and its role in the rehabilitation of wetlands. In: Streever WR (ed) An international perspective on wetland rehabilitation. Kluwer Academic Publishers, Dordrecht, pp 232–243

Cole PG, Weltzin JF (2004) Environmental correlates of the distribution and abundance of *Microstegium vimineum*, in east Tennessee. Southeast Nat 3:545–562. doi:10.1656/1528-7092(2004)003[0545:ECOTDA]2.0.CO;2

D'Antonio CM, Meyerson LA (2002) Exotic plant species as problems and solutions in ecological restoration: a synthesis. Restor Ecol 10:703–713. doi:10.1046/j.1526-100X.2002.01051.x

D'Antonio CM, Vitousek PM (1992) Biological invasions by exotic grasses, the grass fire cycle, and global change. Annu Rev Ecol Syst 23:63–87

Dahl T (1990) Wetlands losses in the United States 1780s to 1980s. U.S. Department of the Interior, Fish and Wildlife Service, Washington, 13 pp

Dahl TE (2006) Status and trends of wetlands in the conterminous United States 1998 to 2004. U.S. Department of the Interior; Fish and Wildlife Service, Washington, 112 pp

Ehrenfeld JG (2003) Effects of exotic plant invasions on soil nutrient cycling processes. Ecosystems (N Y, Print) 6:503–523. doi:10.1007/s10021-002-0151-3

Elton CS (1958) The ecology of invasions by animals and plants. Muthuen, London

Fairbrothers DE, Gray JR (1972) *Microstegium vimineum* (Trin.) A. Camus (Gramineae) in the United States. Bull Torrey Bot Club 99:97–100. doi:10.2307/2484205

Gibson DJ, Spyreas G, Benedict J (2002) Life history of *Microstegium vimineum* (Poaceae), an invasive grass in southern Illinois. J Torrey Bot Soc 129:207–219. doi:10.2307/3088771

Hefner J, Wilen B, Dahl T, Frayer W (1994) Southeast wetlands: status and trends, mid-1970s to mid-1980s. U.S. Department of the Interior, Fish and Wildlife Service, Atlanta, 32 pp

Hobbs RJ, Humphries SE (1995) An integrated approach to the ecology and management of plant invasions. Conserv Biol 9:761–770. doi:10.1046/j.1523-1739.1995.09040761.x

Hooper DU, Vitousek PM (1998) Effects of plant composition and diversity on nutrient cycling. Ecol Monogr 68:121–149

Kennedy TA, Naeem S, Howe KM, Knops JMH, Tilman D, Reich P (2002) Biodiversity as a barrier to ecological invasion. Nature 417:636–638. doi:10.1038/nature00776

Kruskal JB (1964) Nonmetric multidimentional scaling: a numerical method. Psychometrika 29:115–129. doi:10.1007/BF02289694

Legendre P, Legendre L (1998) Numerical ecology, 2nd edn. Elsevier Science BV, Amsterdam, 853 pp

Mack RN, Simberloff D, Lonsdale WM, Evans H, Clout M, Bazzaz FA (2000) Biotic invasions: causes, epidemiology, global consequences, and control. Ecol Appl 10:689–710. doi:10.1890/1051-0761(2000)010[0689:BICEGC]2.0.CO;2

Mather PM (1976) Computational methods of multivariate analysis in physical geography. Wiley, London, p 532

McCune B, Grace JB (2002) Analysis of ecological communities. MjM Software Design, Gleneden Beach, Oregon

McCune B, Mefford MJ (1999) PC-ORD for windows: multivariate analysis of ecological data. MjM Software, Gleneden Beach, Oregon

Mitsch WJ, Gosselink JG (2000) Wetlands. Wiley, New York

Mitsch WJ, Wilson RF (1996) Improving the success of wetland creation and restoration with know-how, time, and self-design. Ecol Appl 6:77–83. doi:10.2307/2269554

Mitsch WJ, Wu XY, Nairn RW, Weihe PE, Wang NM, Deal R, Boucher CE (1998) Creating and restoring wetlands—a whole-ecosystem experiment in self-design. Bioscience 48:1019–1030. doi:10.2307/1313458

Mulhouse JM, Galatowitsch SM (2003) Revegetation of prairie pothole wetlands in the mid-continental US: twelve years post-reflooding. Plant Ecol 169:143–159. doi:10.1023/A:1026221302606

National Wetlands Policy Forum (1988) Protecting America's wetlands: an action agenda. Conservation Foundation, Washington

Oswalt CM, Oswalt SN, Clatterbuck WK (2007) Effects of *Microstegium vimineum* (Trin.) A. Camus on native woody species density and diversity in a productive mixed-hardwood forest in Tennessee. For Ecol Manage 242:727–732. doi:10.1016/j.foreco.2007.02.008

Redman DE (1995) Distribution and habitat types for Nepal *Microstegium* in Maryland and the district of Columbia. Castanea 60:270–275

Seabloom EW, Van der Valk AG (2003) Plant diversity, composition, and invasion of restored and natural prairie pothole wetlands: implications for restoration. Wetlands 23: 1–12. doi:10.1672/0277-5212(2003)023[0001:PDCAIO]2.0.CO;2

Tilman D (1997) Community invasibility, recruitment limitation, and grassland biodiversity. Ecology 78:81–92

USDA (2005) Plants profile; *Microstegium vimineum* (Trin.) A. Camus. In: Plants database. United States Department of Agriculture. Available via. http://www.plants.usda.gov/java/nameSearch?keywordquery=microstegium+vimineum&mode=sciname. Accessed 15 Jan 2005

USDA (2008) Plants database. United States Department of Agriculture. Available via. www.plants.usda.gov. Accessed 4 Apr 2008

Van der Valk AG (1998) Succession theory and restoration of wetland vegetation. In: McComb AJ, Davis J (eds) Wetlands for the future. Gleneagles Publishing Adelaide, Australia, pp 657–667

WSSA (2008) Composite list of weeds. Weed Science Society of America. Available via. http://www.wssa.net/Weeds/ID/WeedNames/namesearch.php. Accessed 4 Apr 2008

Zedler JB, Callaway JC (1999) Tracking wetland restoration: do mitigation sites follow desired trajectories? Restor Ecol 7:69–73. doi:10.1046/j.1526-100X.1999.07108.x

Zedler JB, Kercher S (2004) Causes and consequences of invasive plants in wetlands: opportunities, opportunists, and outcomes. Crit Rev Plant Sci 23:431–452. doi:10.1080/07352680490514673