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Fire and the invasive annual grass *Microstegium vimineum* in eastern deciduous forests

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Abstract

Non-native plant invasions have the potential to change natural and prescribed fire regimes by increasing fuel loads, continuity of fuels, and fuel composition, which may alter fire intensity, damage native species, and promote further invasions. In this project we sought to evaluate the interaction between fire and the invasive annual grass *Microstegium vimineum* in eastern deciduous forests. Our goal was to determine if invasions enhance fire intensity, including fire temperatures, flame heights, and fire duration, and negatively affect tree regeneration, and stimulate further invasions. We also sought to determine how prescribed fires and the timing of fires affect the density and demography of *Microstegium* and we tested the pre and post-fire management options for controlling the post-fire spread of *Microstegium* invasions.

At Big Oaks National Wildlife Refuge in southeastern Indiana, we conducted large-scale prescribed fires to evaluate fire intensity in invaded and uninvaded areas and the response of experimental and naturally regenerating trees. In small-scale plots we manipulated the timing and frequency of fires and applied herbicide treatments to evaluate demographic responses of *Microstegium*. Our results show that maximum fire temperatures were on average 57% greater in *Microstegium*-invaded than uninvaded control areas. In addition, fires burned at temperatures over 300 °C for nearly twice as long and flame heights were 98% higher in invaded compared to uninvaded habitats. *Microstegium* invasion reduced survival of experimental trees by 37% in areas exposed to prescribed fire compared to uninvaded areas and tree survival in invaded, burned plots was 53% lower than invaded, unburned plots. Exposure to prescribed fire increased natural tree regeneration overall but there were 60% and 57% fewer tree seedlings in burned and unburned invaded plots, respectively, compared to control plots with the same treatments. Prescribed fire increased *Microstegium* biomass by five-fold the following growing season.

Experimental spring fires significantly reduced *Microstegium* seedling numbers by ~75% immediately after the burn, but this did not result in reduced seed production at the end of season or seedling numbers the year following a burn. Burning for two springs in a row similarly reduced seedling numbers during each of the years when the burns were conducted, but this effect did not carry over to reduce *Microstegium* seedling numbers the following year. Similarly, fall fire reduced seedling numbers by ~50% the following spring, but this reduction also did not result in reduced seed production at the end of that season. The significant effects on seedling numbers but lack of effect on *Microstegium* seed production was likely due to growth compensation by the surviving plants. Grass-specific, post-emergent herbicide applied without fire was very effective at reducing population numbers, almost eradicating *Microstegium* populations, but fire reduced herbicide effectiveness.

The results of this research demonstrate significant effects of a non-native grass invasion on fire intensity, tree regeneration, and subsequent invasions in eastern deciduous forests, an ecosystem where this phenomenon has not previously been observed. Fire was not useful as a management strategy for *Microstegium* invasions and interfered with an otherwise effective post-emergent herbicide. To avoid the damaging effects of intense fires in invaded areas, we recommend land managers use herbicides or other treatments to remove invasions prior to the application of prescribed fires.

Background and Purpose

Invasions of non-native plants can alter natural fire regimes by changing fire intensity and frequency, the continuity of fuels, and the fire return cycle (Brooks et al. 2004). These changes have been shown to promote further plant invasions by decreasing competition with native species, exposing bare ground, and increasing soil nutrients, resulting in a positive fire-invasion feedback (Vila et al. 2001, Rossiter et al. 2003, Brooks et al. 2004, Brys et al. 2005, Jacquemyn et al. 2005). Furthermore, increases in fire frequency and severity due to climate change may enhance fire-invasion feedbacks, and accelerate the rate at which landscapes are invaded (Grigulis et al. 2005).

Although there are extensive invasions of non-native plant species in the eastern U.S., and many eastern systems are exposed to prescribed and natural fires, relatively little research has addressed the interaction between fire and plant invasions in these systems. In this project we evaluated the interaction between fire and the invasive grass *Microstegium vimineum* (stiltgrass), a species that is rapidly invading forests in the eastern U.S. Our hypothesis was that fire in *Microstegium*-invaded areas would initiate a fire-invasion cycle that would cause significant damage to native species and promote further *Microstegium* invasions (Fig. 1, Brooks et al. 2004). Unlike native understory plant communities in eastern forests, *Microstegium* produces relatively abundant biomass and is slow to decompose following fall senescence (Ehrenfeld et al. 2001). We proposed that this resulted in a continuous bed of fine, highly flammable fuels. We expected that because of this shift in litter quantity and quality, the temperature, continuity, and extent of fires would be enhanced in invaded areas, causing greater damage to native trees and herbaceous species (Hughes et al. 1991). We expected that the effects of fires would subsequently promote *Microstegium* germination, growth and spread (Fig. 1, Glasgow and Matlack 2007). Alternatively, removal of *Microstegium* litter by fire may actually increase native abundance and diversity, as reduced light availability is one major way *Microstegium* suppresses growth of competitors (Belote and Weltzin 2006).

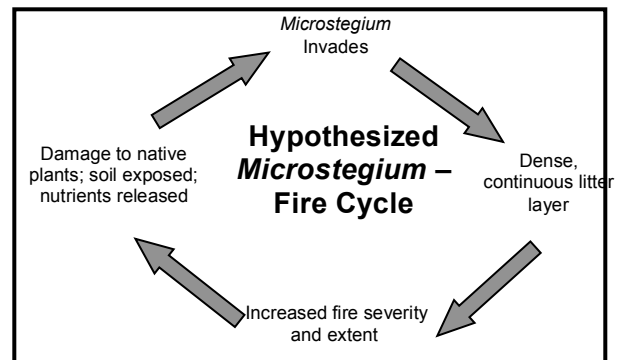
Objectives

The overall objective of this project was to examine the interaction between fire and *Microstegium* invasions in eastern deciduous forests by conducting experimental research at both large and small spatial scales. Our goal was to answer the following specific questions:

- How do *Microstegium* invasions alter fire intensity?
- Do changes in fire intensity in *Microstegium*-invaded areas alter the effects of fire on tree regeneration or native herbaceous species?
- How do prescribed fires and the timing of fires affect the density and demography of *Microstegium*?
- What are the pre and post-fire management options for controlling the post-fire spread of *Microstegium* invasions?

We hypothesize that fire intensity, including temperatures and flame heights, would be enhanced

Figure 1.



in *Microstegium*-invaded areas, thereby reducing tree regeneration and native herbaceous species productivity and diversity, and promoting more dense and widespread *Microstegium* invasions (Figure 1). We further hypothesized that fall burns will be more successful for managing *Microstegium* invasions than spring burns because *Microstegium* seeds germinate readily following spring fires (Glasgow and Matlack 2007). Finally, we predicted that post-fire application of a pre-emergent herbicide or growing season application of post-emergent herbicides would help to suppress *Microstegium* in burned areas.

Background

Low-intensity, quickly moving fires were historically common in eastern deciduous forests. Relatively frequent fires helped to maintain oak-hickory dominated forest communities, remove built-up litter, and regulate herbaceous community diversity and productivity (McEwan et al. 2007). Fires are now less common in eastern forests but natural fires do still occur and prescribed fires are being used in many forests to maintain historically accurate plant communities or to promote the dominance of particular plant species or communities.

In other ecosystems, the introduction of certain non-native invasive plant species has been shown to enhance fire intensity, alter the effects of fires on native species and processes, and often promote further invasions of non-native species (e.g. Rossiter et al. 2003, Brys et al. 2005, Jacquemyn et al. 2005). In the submontane zone of Hawaii, for example, invasions of non-native grasses (*Andropogon*, *Melinis*, and *Schizachyrium* spp.) significantly increased the frequency and extent of fires, which promoted more widespread grass invasions and reduced the cover and diversity of native shrub and tree populations (Hughes et al. 1991). In the western U.S., invasions of non-native annual grasses (e.g. *Bromus* spp.) have increased the frequency, intensity, and extent of fires. Annual grass invasions produce abundant, highly flammable fuel loads that carry fire quickly and continuously, resulting in the decline of native shrubs and perennial grasses (reviewed by D'Antonio and Vitousek 1992). In addition, fires can have a fertilizing effect when nitrogen and other nutrients are released from burned material, further contributing to the spread of non-native grasses and instigating a grass-fire cycle that is difficult to break (D'Antonio and Vitousek 1992). Given the results of these studies, it is clear that the interaction between fires and invasive non-native plants can have substantial effects on fire behavior and the spread of invasive plants. However, very little research has been conducted on the interaction between invasive non-native plant species and fire in eastern deciduous forests, where certain plant invasions may be having similar effects on fire behavior and its impacts.

While fire is often a viable management option to control fire-intolerant invasive species in the eastern US (e.g., Emery and Gross 2005, Nuzzo et al. 1996), non-native grass invasions can present unique challenges to fire-managed systems. One situation of particular concern related to fire behavior is the invasion of forests in the eastern U.S. by the non-native annual grass *Microstegium vimineum* (Trin.) A. Camus (stiltgrass; hereafter *Microstegium*). It is one of the most aggressive and problematical plant invaders in eastern North America. It colonizes roadsides, trails, and disturbed areas, but can also invade intact forests and riparian areas (Barden 1987, Cole and Weltzin 2004, Flory 2010). *Microstegium* is unusual because it is a C4 species that can tolerate extremely low light levels in closed-canopy forests (Flory et al. 2007, Flory 2010, but see Cole and Weltzin 2005). It forms a dense litter layer where cleistogamous seeds are dispersed in dead stems (Cheplick 2006). Further, *Microstegium* is highly plastic and can quickly alter its phenotype based on environmental conditions (Claridge and Franklin 2002, Droste et al. 2010). *Microstegium* was first documented in Tennessee in 1919 (Fairbrothers and Gray 1972) but for many decades was not recognized as an

invasive species. However, over the last 20 years it has spread rapidly with large, dense infestations throughout much of the eastern US, and rapid spread to the north and west. It is currently found in more than 22 states in the eastern and southern U.S. and is quickly spreading to the north and west.

We have recently documented dramatic ecological effects of *Microstegium* on native communities (Flory and Clay 2010a, b, Simao et al. 2010, Bauer and Flory 2011). Addition of *Microstegium* to large, replicated field plots reduced native herbaceous biomass, richness and diversity (Flory and Clay 2010a), and tree seedling establishment (Flory and Clay 2010b). Further, removing *Microstegium* in natural communities with a grass-specific herbicide significantly increased native herbaceous biomass and diversity, and tree regeneration (Flory and Clay 2009, Flory 2010). Invasions also negatively affect arthropods (Civitello et al. 2008, Simao et al. 2010), and can alter ecosystem processes such as nitrogen (Lee et al. 2012) and carbon cycling (Strickland et al. 2010), and decomposition (Ehrenfeld et al. 2001).

Microstegium produces abundant biomass and it is slow to decompose following fall senescence, resulting in a dense mat of dry vegetation (Ehrenfeld et al. 2001). In an earlier study (funded by the USFS), we evaluated multiple treatment options for removing *Microstegium* invasions, and found that across eight sites, invaded plots had an average of 247% greater plant biomass than plots where *Microstegium* had been experimentally removed (Flory 2010). Abundant, senesced *Microstegium* may enhance the intensity, spread, and frequency of fires by producing a highly flammable, continuous bed of fine, dry fuels. Consequently, intense and widespread fires in areas invaded by *Microstegium* may damage native herbaceous and woody plants more than areas that are not invaded. In addition, fires may decrease natural litter layer depth, increasing mineral soil exposure resulting in increased germination rates and more dense and widespread *Microstegium* invasions (Fig. 1, Glasgow and Matlack 2007). Alternatively, fires may be capable of slowing *Microstegium* growth if fire season is altered to target reproductive plants when native plants are dormant. In a small study comparing effects of spring and fall burns, weeding, and mowing on *Microstegium*, we found that fall burns and mowing were effective at reducing *Microstegium* biomass by 90% and 95% respectively the following spring, while spring burns (49% reduction) and hand weeding (19% reduction) were much less effective (Flory and Lewis 2009). However, it is not known how these management practices affect *Microstegium* invasions over multiple years. This is the first project to address the interaction between fire and *Microstegium* and their effects on fire behavior, tree regeneration, and native plant diversity at a large scale.

Study Location and Description

Study location

We conducted this study at the 20,647 ha Big Oaks National Wildlife Refuge (BONWR) in southeastern Indiana. BONWR, a former military testing facility, is one of the largest contiguous forest/grassland complexes in the Midwest and is the largest national wildlife refuge in Indiana. BONWR contains extensive invasions of *Microstegium* in both upland and lowland sites. Sites included forests at varying stages of succession from young forests that were abandoned from management within the last 20 years to mature, closed canopy forests. All sites had some history of prior (<60 years) anthropogenic disturbances including prescribed fire and timber harvests. Sites were predominantly uneven-aged mixed deciduous forest consisting of American beech (*Fagus grandifolia*), black walnut (*Juglans nigra*), red maple (*Acer rubrum*), sweet gum (*Liquidambar styraciflua*), tulip poplar (*Liriodendron tulipifera*), and sycamore (*Platanus occidentalis*). Understory communities were dominated by spicebush (*Lindera benzoin*), *Viburnum* spp., and greenbriar (*Smilax* spp.).

Methods

To address our research questions we conducted two main experiments. In the first experiment, we established large-scale plots in *Microstegium*-invaded and uninvaded areas throughout BONWR and either exposed the areas to regularly-scheduled (2-4 year return interval) prescribed fires or not. In the second experiment, we established a series of small-scale experimental plots at five sites at BONWR and exposed them to eight treatments (6 replicates per site, 240 total plots) including spring and fall fires and post-emergent and pre-emergent herbicides.

Experiment 1: Large-scale prescribed fires in invaded and uninvaded areas

We used this experiment to determine: 1) How *Microstegium* invasions affected fire intensity and 2) How invasions and fire affected tree regeneration and native herbaceous species.

During fall 2008 and 2009, we selected research sites in BONWR units scheduled to be burned in spring 2009 and 2010. Burn units at BONWR range in size from 10 to 1,000 ha and include mixed grasslands, old fields, and secondary and mature forests. Because *Microstegium* invasions occur in many types of habitats (e.g., lowland forest, upland forest, forest openings, and along forest-field edges), we included sites with a wide variety of characteristics. Within each burn unit we located one plot in an area invaded by *Microstegium* and then searched for the nearest site with similar slope, aspect, elevation, plant communities, and overstory composition and density that was not invaded by *Microstegium* or contained very few *Microstegium* plants (<10% cover). Sometimes the “paired” plot was located very nearby (<50m) but other times we had to locate the plot 100-400 m distant. However, regardless of the proximity of the paired plot, the plots were burned during the same prescribed fire event and were therefore exposed to similar weather and fuel moisture conditions. In total, we established 14 plots (10 m x 15 m) in fall 2008 and 12 additional plots in separate areas in fall 2009 that we planned to expose to prescribed fire. To compare tree regeneration and herbaceous community responses in burned areas to areas not exposed to fire, we also established 6 plots in invaded areas and 6 plots in uninvaded areas that were not scheduled to be burned during the time frame over which we conducted the experiment. We used the same criteria to identify these plots and they had similar habitat characteristics as those in burned areas.

To evaluate the effects of fire and invasions on tree regeneration and to control for the size, number, and species of trees in the plots, we experimentally planted trees in each of the plots in early fall 2009 and 2010. We used nursery-grown bare-root stock of two fire tolerant species (*Quercus alba* and *Quercus velutina*) and two relatively fire intolerant species (*Acer rubrum* and *Liriodendron tulipifera*). *Quercus macrocarpa* was used in place of *Quercus velutina* in 2009 plantings due to limited seedling availability. We planted one individual of each species at six locations in each plot and measured seedling diameter, height, and survival at planting and after prescribed burns were conducted. We also identified and counted all naturally occurring tree seedlings in ten 1 m x 1 m subplots in each plot. Finally, we conducted destructive harvests at six locations in each plot at the end of the growing season the year prior to the fires to characterize *Microstegium* and native herbaceous plant communities.

Immediately prior to each fire we collected samples from each plot to evaluate fine fuel abundance, composition, and moisture content. Then, during fires we measured fire temperatures using type K thermocouples and HOBO data loggers, flame heights using passive flame height sensors (flame retardant soaked string), and took photographs and video. Temperature was measured at six locations in each plot, immediately adjacent to the experimentally planted tree seedlings, and

12 flame height measurements were recorded. Following fires we evaluated the percent area burned in six separate 1 m x 1 m areas in each plot. Then, in the fall we repeated the destructive vegetation harvests at six locations in each plot, and counted, identified, and measured tree seedlings to gauge plant community responses to fire and *Microstegium* invasion. In late winter the following year we evaluated the survival, diameter, and height of the experimentally planted tree seedlings.

Experiment 2: Small-scale experimental fires in invaded areas

We used this experiment to determine: 1) How fire and the timing of fires affect the density and demography of *Microstegium* and 2) The pre and post-fire management options for controlling the post-fire spread of *Microstegium* invasions.

In fall 2008 we established 60 2 m x 2 m plots at each of six *Microstegium*-invaded sites at BONWR. Each plot was randomly assigned to one of 10 burn treatments (spring 2009, fall 2009, spring 2010, fall 2010, spring 2009+2010, fall 2009+2010, and no burn) or three herbicide treatments (pre-emergent + fire, post emergent, post emergent + fire). Due to adverse weather conditions we were not able to conduct the fall 2010 experimental fires so the fall 2010 and the fall 2010 + fall 2009 treatments were dropped from the analysis. In addition, one site was mostly burned over by an escaped fire and was abandoned.

Fires were conducted in late March and early April in the spring and in October in the fall. Fires were initiated with drip torches and contained and extinguished with pump backpack sprayers and hand tools. The pre-emergent herbicide treatment consisted of 1.34 kg ai/ha of pendimethalin (19.2 oz/ac Pendulum AquaCap; BASF, Research Triangle Park, NC) and was applied in spring just prior to the fires. The post-emergent herbicide treatment was 0.21 kg ai/ha of fluazifop-P-butyl (12 oz./ac Fusilade DX; Syngenta Crop Protection, Inc., Greensboro NC) mixed with 14.8 ml of a nonionic adjuvant surfactant (Surf Plus 584, Townsend Chemical Division, Muncie, IN) and was applied in early June. Both herbicides were applied with backpack sprayers at 40 psi.

Microstegium population characteristics as well as native plant community characteristics were evaluated in all plots using destructive harvests. *Microstegium* population dynamics were intensively monitored at each life history stage in 25 cm x 25 cm subplots in each plot. Each year, *Microstegium* seedling and adult stem density was measured in each plot and reproduction was estimated as number of seeds produced per area. Seed bank dynamics in each plot were estimated by collecting three 5 cm x 5 cm soil cores per subplot, planting them in the greenhouse under ideal conditions, and repeatedly monitoring them over the next 6-8 months to count emergent seedlings (TerHeerd et al. 1996). By returning to the same plots to collect data at each life stage, we were able to construct life tables to calculate the effects of fire, the timing and frequency of fires, and herbicide treatments on *Microstegium* population growth rate λ (Emery and Gross 2005).

Key findings

Experiment 1: Microstegium invasions increase fire intensity and reduce tree regeneration

Our results showed that fires in *Microstegium*-invaded areas had higher peak temperatures, burned longer at higher temperatures, and had significantly higher flames than in nearby uninvaded areas. Across the 2009 and 2010 spring prescribed fires, which did not differ in fire intensity characteristics, the maximum fire temperatures were on average 57% greater in invaded (mean \pm SE; 698.1 \pm 46.4 °C) than uninvaded (398.2 \pm 48.1 °C) areas. Furthermore, fires in *Microstegium*-invaded areas burned at temperatures over 300 C for nearly twice as long as fires in uninvaded habitats (mean \pm

SE; invaded 15.3 ± 1.9 sec vs. uninvaded 7.8 ± 1.96 sec). Flame heights in invaded areas were 98% higher in invaded (32.2 ± 7.7 cm) compared to uninvaded (16.3 ± 3.6 cm) areas. A greater percentage of the invaded habitats tended to burn than in uninvaded areas, possibly because the contiguous coverage of *Microstegium* consistently carried the fires, but this difference was not statistically different. We hypothesized that greater fire intensity in invaded areas would be driven by higher mass of fine fuels. Surprisingly, the abundance of fine fuels in invaded and uninvaded habitats was equivalent. There were also no differences in fuel moisture. It was not possible to separate fuels based on *Microstegium* and native species, but equivalent fuel mass measurements could have been the result of *Microstegium* replacing resident native species (Flory 2010, Flory and Clay 2009). Instead, the differences in fire behavior in invaded areas may have been due to differences in fuel characteristics. Senesced *Microstegium* consists of fine stems that are loosely arranged with abundant air spaces. In contrast, fuels in native-dominated areas may have been more densely packed, resulting in less intense fires. Alternatively, fuel abundance may have differed in invaded and uninvaded areas but our limited sampling was not able to detect those differences.

More intense fires in invaded areas had dramatic consequences for the survival of experimentally planted trees. Across all tree species, there was an interaction between the invasion and prescribed fire treatments. On average, invasion status did not significantly affect survival of trees in unburned control plots but *Microstegium* invasion reduced tree survival by 37% in areas exposed to prescribed fire compared to uninvaded areas. Moreover, tree survival in invaded, burned plots was 53% lower than invaded, unburned plots. This pattern of greatly reduced tree survival due to the invasion/fire interaction was consistent across all experimentally planted tree species. There was a similar pattern of effects for tree growth (i.e., final basal diameter) where burning reduced growth overall but the diameter of surviving trees in *Microstegium*-invaded areas exposed to fire was 38% less than trees in uninvaded burned areas.

Fire and *Microstegium* invasion also affected the number of trees naturally regenerating from seed. Fire promoted tree seedling establishment in uninvaded control plots by 38% and in invaded plots by 165%. The greater increase in tree regeneration in invaded plots may have been due to the release from the suppressive effects of the abundant thatch layer that often accumulates in *Microstegium*-invaded areas (Flory and Clay 2010b). Despite this greater relative increase in tree regeneration due to exposure to prescribed fire, there were 60% and 57% fewer tree seedlings in burned and unburned invaded plots, respectively, compared to control plots. Thus, fire promoted tree regeneration across both invaded and uninvaded habitats but *Microstegium* invasions greatly suppressed natural tree regeneration.

One of the key aspects of the fire-*Microstegium* feedback cycle we proposed is that greater invader abundance and subsequently increased fire intensity would result in greater relative abundance of invasive *Microstegium*. Supporting this prediction, we found that prescribed fires in invaded areas increased *Microstegium* biomass by nearly 500% the following growing season as compared to what was found in those plots the year prior. In contrast, control areas not exposed to fire actually declined in *Microstegium* abundance over the same time period, possibly due to unfavorable growing conditions (e.g., drought) during the 2010 growing season.

As a follow up to the field study, we conducted a lab experiment to compare the effects of fire temperatures on germination rates of six native and three non-native forest understory species. We manipulated both fire intensity (temperature and length of exposure) and type of fire effect (direct flame and indirect furnace heat) to generate germination curves and make predictions about potential prescribed fire effects on populations of these species. Germination of three native species, *Lycopus americana* (American water horehound), *Verbesina alternifolia* (wingstem), and *Vernonia gigantea* (tall ironweed), showed signs of being stimulated by heating at low temperatures, while

germination of all non-native species (*M. vimineum*, *Elaeagnus umbellata*, and *Schedonorus phoenix*) were inhibited at these lower intensities. High fire intensity (temperatures above 300 °C) effectively killed most seeds of all species. We conclude that high-intensity prescribed fires in habitats invaded by *Microstegium* may reduce seed germination of some non-native species, but may also inhibit the regeneration of native understory species (Emery et al. 2011).

Experiment 2: Effects of fires and herbicide treatments on the density and demography of Microstegium populations

The various fire treatments in the small-scale experimental burn plots often reduced seedling numbers but did not have long-term consequences for *Microstegium* population dynamics. Spring fires significantly reduced seedling numbers by ~75% immediately after the burn, but this did not result in reduced seed production at the end of season, and did not affect seedling numbers the year following a burn. Burning for two springs in a row (2009 and 2010) similarly reduced seedling numbers during each of the years when the burns were conducted, but this effect did not carry over to reduce seedling numbers in 2011. Similarly, the fall burn in 2009 reduced seedling numbers by ~50% the following spring, but this reduction also did not result in reduced seed production at the end of that season. The significant effect on seedling numbers but lack of effect on seed production was likely due to growth compensation by the surviving plants. Individual plants in smaller populations were able to produce more seeds per plant than in denser populations, which negated most of the effects that burning had on seedling numbers. Overall, there was a natural decline in population numbers in reference plots from 2008 to 2010, which was possibly due to drought or other environmental factors unrelated to the experimental treatments.

Herbicides were very effective at reducing population numbers, especially the treatment where post-emergent herbicide was applied without fire, which almost completely eradicated *Microstegium* populations. Fall fire seemed to negate some of the benefits of herbicide, though population numbers were still 85% lower than in untreated reference plots. Pre-emergent herbicide that was applied in the spring and then followed by spring fire reduced seedling numbers and seed production during the year of application, though this effect did not carry through to the following year.

Periodic matrix population models showed that 2009 treatments were effective at reducing population growth rates in 2009, but this did not carry over to reduce 2010 growth rates. Elasticity analysis showed that survival of seeds in the seedbank was the most important transition controlling population growth. While seedbank numbers differed among treatments, this was generally restricted to single-year effects only (similar to treatment effects on seedling numbers), and the limitations of this study did not allow us to examine seed longevity in the seedbank.

Management Implications

Experiment 1: Microstegium invasions increase fire intensity and reduce tree regeneration

This project was originally motivated by land manager observations that prescribed fires in *Microstegium*-invaded areas often resulted in especially intense fires and greater abundance of the invader. Here we found that fires in invaded areas resulted in higher peak fire temperatures, fires that burned hotter long, and taller flame heights. More intense fires could have been the result of altered fuel properties in invaded areas where senesced *Microstegium* creates a loose fuel bed with abundant air spaces. The increased fire intensities we observed in *Microstegium*-invaded areas resulted in significantly reduced survival of experimental tree seedlings. Furthermore, invasions greatly

inhibited natural tree regeneration.

Microstegium has a widespread and increasing distribution and now occurs in 25 states in a variety of forested habitats, thus these results have important implications for natural areas management throughout much of the eastern US. From previous research (Flory and Clay 2010b) we knew that invasions suppressed tree regeneration and that the inhibition of trees varied among species such that invaded forests and successional habitats might eventually shift in species composition due to the invasion. Separately, prescribed fire is used for habitat management, including encouragement of oak regeneration (Iverson et al. 2008) in eastern deciduous forests. Our results suggest that the use of such prescribed burns in invaded habitats should be minimized or conducted with great caution. Ideally, invasions should be eliminated with grass specific herbicides (Flory 2010) prior to conducting prescribed fires to encourage tree regeneration.

We found that on average prescribed fires caused a five-fold increase in *Microstegium* abundance. This result suggests that fires may promote a positive grass-fire feedback cycle (Fig 1.) similar to what has been observed in Hawaiian and Mediterranean ecosystems. Clearly invasions can cause unusually intense fires and have significant impacts on native species. The fact that fires also encourage higher density invasions means that invasions may spread more rapidly following fires. Thus, fire-invasion interactions may result in more widespread invasions, more intense fires, and further impacts on tree survival and regeneration. In sum, our research indicates that the interactive effects of fire and *Microstegium* invasions may have dramatic consequences for the composition and long-term dynamics of eastern deciduous forests.

Experiment 2: Effects of fires and herbicide treatments on the density and demography of Microstegium populations

Based on the results of this study, we recommend use of post-emergent, grass-specific herbicides for controlling *Microstegium* invasions. This confirms our earlier findings that such herbicides can be highly effective at reducing population sizes (Flory 2010). We also found in our earlier work that grass-specific herbicide is the most effect treatment option to encourage recovery of native species abundance and diversity and to promote tree regeneration (Flory and Clay 2009). Here we found that fire may actually cancel out some of the benefits of herbicide such that *Microstegium* populations recover faster when fire is applied after herbicides. Together with our results from the prescribed fire study showing higher abundance of the invader following fire, we recommend that fire be avoided as a management tool for *Microstegium* control. However, fires that benefit the native plant community may be combined with post-emergent herbicide to still reduce *Microstegium* population sizes. Further research is required to determine the circumstances under which this combination of treatments will be most effective.

Relationship to other recent findings and ongoing work

Previous research has demonstrated that in some systems invasive plants may be encouraged by fire, sometimes initiating a positive feedback cycle (Dantonio and Vitousek 1992). However, in other cases prescribed fires have been used to effectively manage plant invasions and encourage native plant recovery (DiTomaso et al. 2006). Most systems where positive grass-fire cycles have been observed are semi-arid or at least seasonally dry. Here, we found that invasion by a non-native annual grass in temperate deciduous forests may also initiate a similar grass-fire cycle that results in increased fire intensity, suppressed native species, and further invasions.

The fire-invasion interaction we observed in this study was similar to what has been observed previously in other ecosystems, and the effects were at least as large if not greater, but the context under

which the interaction occurred (temperate deciduous forest) was unique. Ongoing work in other systems will help to determine the species and habitats under which fire will promote invasions and situations where fire can be used to help control unwanted species and restore habitats. Although previous work has shown that *Microstegium* establishment may be promoted by fire (Glasgow and Matlack 2007) our study is the first comprehensive study of *Microstegium* population dynamics under landscape-scale prescribed fire conditions and the first to examine the effects of *Microstegium* invasions on fire behavior and tree regeneration.

Previously we showed that *Microstegium* cover could be reduced by nearly 80% and biomass by 90% by applying fall fires. We also found that spring fires could significantly reduce invader cover but not biomass (Flory and Lewis 2009). However, in that study we applied spring fires in June and fall fires in early September instead of during late March or early April in the spring and in mid to late October in the fall as we did in this study. In addition, in the previous study we used a propane torch to burn actively growing *Microstegium*, whereas here we used fires that carried naturally through senesced plant material. Thus, although we previously showed effective control when burning live *Microstegium*, applying fire outside of the growing season promotes or does not affect *Microstegium* population dynamics. This difference highlights the need to examine the use of fire during both the growing and dormant seasons.

Future Work Needed

Our goal with this project was to evaluate all aspects of the grass-fire cycle for *Microstegium* invasions. We were able to examine effects of invasions on fire behavior, the impacts of fire and invasions on tree regeneration, and the demographic and biomass responses of *Microstegium*. However, a key experiment that we were not able to complete, despite two separate attempts that were halted by unfavorable weather, was to quantify the effects of fire on establishment of new invasions in novel habitats. Thus, there is a primary need for future experiments that can determine the effects of fires on the spatial extent of invasions at the landscape scale.

While we found that seed bank numbers differed among treatments, the responses were generally limited to single-year effects, similar to the treatment effects on seedling numbers. We were restricted in the amount of time over which we could conduct our demography experiment and plots and sampling subplots were of small scale. Therefore, there is a need for future seed bank research to be performed over much longer time frames and larger areas to evaluate the roles of spatial and temporal heterogeneity. For example, seed bank, and thus invasion dynamics, may vary under different weather conditions in different years or in different habitats than we evaluated in our experiments.

In successive years we attempted to measure the effects of invasions on fall fire behavior but were limited by wet weather conditions. Fall fires in Indiana and throughout much of the area over which eastern deciduous forest occurs are conducted only in especially dry years. In other years, precipitation is too frequent or conditions are too overcast and humid to dry fuels to appropriately low moisture levels. However, in years when fires are possible, land managers report that large areas can be burned and that fires are much more intense in forested areas than spring prescribed fires. Such differences in fire intensity and behavior are likely due to the fact that fuels have not been compressed by snow, ice, rain, or wind as with fuels in spring fires, and little decomposition has taken place. We would expect that fuel packing may have particularly strong effects on the flammability of *Microstegium*. Thus, fall fires may show even greater differences between invaded and uninvaded areas than spring fires and even greater effects on tree regeneration. Future research should focus on evaluating fall fire behavior and ecosystem responses in *Microstegium*-invaded areas.

Although our experiments were conducted over a wide range of habitat conditions, from nearly

closed canopy forests to forest openings with few mature trees, fire-invasion interactions may differ in other habitats and in other geographic areas. *Microstegium* now occurs in 25 states in the U.S. in a wide variety of habitats. We recently showed experimentally that *Microstegium* can establish in habitats with environmental conditions even more diverse than where we typically observe invasions (Flory et al. 2011). In addition, “in-filling” of *Microstegium* invasions continues to occur across the invaded range. This suggests that *Microstegium* invasions will continue to expand spatially and occur in areas exposed to prescribed fires. Finally, there is a need to determine how larger, landscape scale invasions can be managed with herbicide and fire or other efficient and economical treatments. Research on the impacts and management of invasions on fires should be conducted across additional sites with different densities and abundances of *Microstegium* and varying soils, hydrology, and native species composition.

Deliverables Crosswalk Table

Deliverable	Description	Target Audience	Status	Date
Web site	Project description and goals, results, videos of experiment, and suggestions for land managers: florylab.com/fire	Land managers and scientists	Delivered	2008-current
Presentation	Natural Areas Association annual conference, Tallahassee, FL (national)	Scientists and land managers	Delivered	2011
Presentation	Ecological Society of America annual meeting, Albuquerque, NM (international)	Scientists and land managers	Delivered	2009
Presentation	AFE 4 th International Congress: Fire Ecology and Management, Savannah, GA (international)	Scientists and land managers	Delivered	2009
Presentation	Organized session and presentation at the Midwest Invasive Plant Network annual meeting (regional)	Scientists and land managers	Delivered	2008
Presentation	Covering the Ohio River Valley: A Convergence of Media and Scientists Louisville, KY (regional)	Public and land managers	Delivered	2010
Presentation	USDA Interagency Research Forum on Invasive Species, Annapolis MD (national)	Scientists and land managers	Delivered	2010
Webcast training session	Interactive presentation with questions and discussion, hosted by Lisa Brush, (stewardshipnetwork.org)	Land managers	Delivered	2010
Refereed publication	Fire effects on seed germination of native and invasive eastern deciduous forest understory plants, <i>Forest Ecology and Management</i>	Scientists and land managers	Delivered	2011
Refereed publication	Non-native grass invasion alters native plant composition in experimental communities, <i>Biological Invasions</i>	Scientists and land managers	Delivered	2010
Refereed publication	Non-native grass invasion suppresses forest succession, <i>Oecologia</i>	Scientists and land managers	Delivered	2010
Refereed publication	Nonchemical methods for managing Japanese stiltgrass, <i>Invasive Plant Science and Management</i>	Scientists and land managers	Delivered	2009
Refereed publication	Non-native invasive grass increases fire intensity and reduces tree regeneration in eastern forests	Scientists and land managers	<i>In prep</i>	2012
Refereed publication	Interactive effects of prescribed fire and grass invasion on native plant communities	Scientists and land managers	<i>In prep</i>	2012
Refereed publication	Demographic responses of the invasive annual grass <i>Microstegium vimineum</i> to fires and herbicide treatments	Scientists and land managers	<i>In prep</i>	2012
Field tours	Tours of research sites (<i>The Wildlife Society, Indiana Department of Natural Resources, Division of Wildlife, Kentucky Department of Fish and Wildlife Resources, US Fish and Wildlife Service, Natural Resources Conservation Service</i>)	Land managers	Delivered	2009, 2010
Non-refereed publication	Technical report	Land managers	<i>Information delivered via web site</i>	2008-current

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