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White Paper: 2010 Stiltgrass Summit. River to River Cooperative Weed Management Area

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Southern Illinois University, Carbondale August 11-12, 2010

RIVER TO RIVER COOPERATIVE WEED MANAGEMENT AREA

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Acknowledgments

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This publication is dedicated to the memory of Les Mehrhoff (1950-2010). His enthusiasm for conservation and love of nature was as refreshing as it was contagious. Les' involvement was instrumental to the success of the Stiltgrass Summit. It is our hope that we all will honor Les by pausing a moment to take a look at the beauty of nature and, of course, by never forgetting to bring our hand lenses.

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Cover photo:

A secondary oak-hickory forest understory at Dixon Springs State Park, Golconda, Illinois, is invaded by a dense stand of *Microstegium vimineum*. This was the location of one population used to study the life history of the invader (Gibson *et al*., 2002). Researcher Greg Spyreas stands in the background, holding large clumps of *Microstegium*. The photo was taken by Jennifer Benedict, © David J. Gibson.

Executive Summary

Since *Microstegium vimineum* was first identified in Knoxville, TN in 1919, it has spread to 25 states, Puerto Rico, and the District of Columbia, and is still spreading through the movement of water, people, and animals. Land managers and concerned citizens should learn to identify *Microstegium* and report new findings in an effort to help halt the spread of this species. *Microstegium* invasions may change the local habitat and impact other species. While there are few factors that seem to limit invasion, deep leaf litter, shading, dispersal limitation, and low soil moisture availability may control the presence of *Microstegium*. Populations not limited by these factors and located in areas with optimal amounts of available resources, such as those conditions often found at forest edges, may act as a source of propagules to maintain populations that are reproductively limited. The optimal areas for *Microstegium* invasion may also be the sites with the highest richness of native herbaceous plants. In suboptimal environments, which may occur in some forest interiors, *Microstegium* plant height increases, increasing residual thatch after the growing season. This increased thatch may cause an increase in fire intensity, especially where winter precipitation to compact the thatch may be absent. Data show that prescribed fire, experimental disturbance, and flooding increase *Microstegium* seedling recruitment. However, seed from interior populations may not remain viable for as long as seed produced in forest edge habitat. Although seed normally fall close to the mother plant, mesic sites with overland water flow, and sites with low slope or timber harvest had the most rapid rate of spread.

Microstegium invasion affects soil microbial biomass, carbon and nitrogen cycling, and plant community composition and function, although scientific studies have shown a diversity of responses to invasion. Differences in results may indicate a differential response of *Microstegium* to various environmental conditions or may be a product of methodologies. The high C:N ratio of *Microstegium* tissue may be one factor behind community and ecosystem level changes. The presence of arbuscular mycorrhizal fungi (AMF) and saprotrophic fungi may increase, as a result of the greater efficiency of these fungi in extracting nitrogen from tissue with a high C:N ratio. A high C:N ratio may also suggest that *Microstegium* is able to outcompete other plants by having double the nitrogen use efficiency of native forbs, sedges, and grasses. Also, *Microstegium* may alter the plant community composition, impacting forest recovery after disturbance, by producing chemical compounds that inhibit germination and growth of other species. Ecosystem impacts of invasion also include reductions in plant community richness and diversity, overall groundcover, and arthropod richness and abundance. Although plant communities seem to have little resilience to invasion, there are two documented cases of failed invasion, and *Microstegium* has been shown to be a food source for some herbivores and be susceptible to the fungal pathogen, *Bipolaris* sp.

Managing land with a *Microstegium* invasion entails several challenges and considerations. Landscape level models to help land managers predict the trajectory of invasion are being developed. Generally, management programs for *Microstegium* and other invasive species consist of four components: prevention, Early Detection Rapid Response (EDRR), control and management, rehabilitation and restoration. EDRR states that control of an invasive should occur in a strategic response, immediately upon identification in order to prevent high costs and ecological damage. Herbicide may be an important control tool, especially in large-scale invasions. It has been shown that habitats may be restored by using a grass specific herbicide, such as fluazifop-P-butyl or fenoxaprop-P. Sites with optimal environmental conditions for growth and reproduction of *Microstegium* should be given high control priority. Knowledge of plant requirements at each growth stage may be used as a management tool. Work in or passage through invaded areas should be avoided during flowering or seeding, and equipment, boots and clothing should be cleaned after going through an invaded area. A plan for land management needs to be in place prior to invasion. Land managers may benefit by building special considerations for prevention and control of invasive spread into agency contracts.

Introduction

Japanese stiltgrass, *Microstegium vimineum*, is an aggressive invader of various habitat types: forest interiors and edges, flood-prone areas, yards, roadsides, rights-of-way, trails and recreational sites, and federal and state parks, forests, and wildlife management areas. Humans are the most important vector for long-distance dispersal and new introductions, while water is the most important vector for the spread of invasions. Dispersal also occurs with the movement of wildlife. Disturbance facilitates invasion but is not necessary for establishment. *Microstegium* is unlikely to have reached its maximum possible distribution and is predicted to eventually occupy the full extent of the Central Hardwoods Region. Where *Microstegium* invades, there is a loss of native plant species as diversity declines, which has cascading ecological effects. *Microstegium* may also have allelopathic properties and the ability to alter nutrient cycling and availability to other organisms, with associated changes in the soil microbial community. Forests may lose regenerative abilities, as some species of trees may not germinate in infested areas. Additionally, *Microstegium* thatch may change fire regimes, increasing fire intensity. *Microstegium* invasion is difficult to combat, is still spreading rapidly, and may pose serious threats through the permanent alteration of natural systems with possible extirpations or extinctions and economic losses in timber and other forestry related industries.

The 2010 Stiltgrass Summit

This summit was deemed necessary based on the rapid spread of *Microstegium* into new lands and difficultly of control. Invasions encapsulate many complex issues, so that a summit was necessary to bring together many people and organizations with experience and expertise to develop solutions. The River to River Cooperative Weed Management Area (RTRCWMA), a partnership of university representatives, non-profit organizations, and state and federal agencies, with the goal of education, prevention, control, and monitoring of invasive species in Southern Illinois, organized this summit which took place August 11-12, 2010 at Southern Illinois University, Carbondale, Illinois. Summit objectives were to increase attendees' knowledge of *Microstegium* ecology and management by facilitating an exchange of information between academics and land managers, to elaborate upon methods to control and manage *Microstegium*, and to increase the ability of all attendees to combat *Microstegium* invasion. Attendees represented diverse backgrounds, which included private citizens, non-profit and for-profit businesses, other CWMAs, several federal, state, and county agencies, and seven universities – all from 12 states. Summit activities included poster presentations of current research, oral presentations on ecological impacts and management options, panel discussions on control and management with input from all attendees, and field trips to natural areas invaded by *Microstegium*. Key points from the stiltgrass summit and other relevant literature are summarized in this white paper. The reported F-statistics and p-values are taken from the presentations. Entire presentations and panel discussions may be viewed at http://www.rtrcwma.org/stiltgrass. It is the hope of the RTRCWMA that the knowledge gained will be applied and shared with others (Evans, 2010b). A comprehensive review of *Microstegium* in the current scientific literature is available from the USDA website: http://www.fs.fed.us/database/feis/plants/graminoid/micvim/all.html (Fryer, 2011).

Points from the summit

Introduction, spread, and extent

- **There was considerable early interest in comparisons between Japanese and North American flora.** Asian plant species existed in this country before 1853, but it was in this year that Commodore Matthew Perry opened direct North American - East Asian trade routes. Previously, much trade had already occurred, though it was mediated by Europe. Perry's Expedition (1853-1855) was very interested in facilitating an information exchange, so a medical doctor with the expedition, Dr. James Morrow began sending plant specimens for identification to Harvard botanist, Asa Gray, who had already published papers on comparisons between Japanese and North American flora (Gray, 1840, Gray, 1846, Gray, 1859). One of these specimens, which we know very well today as an invasive, is Morrow's honeysuckle, *Lonicera morrowii*. These comparisons remain pertinent today, as we see many of Eastern Asian species which have escaped into our flora, including *Microstegium vimineum* (Mehrhoff, 2010).

- **In 1919 the first documented collection of *Microstegium* occurred by George G. Ainslie.** Ainslie was an entomologist studying grass stem-boring insects, so he made collections of plants and insects. He collected the first specimen of *Microstegium* on the banks of Third Creek in Knoxville, TN, and sent the specimen to the Smithsonian Institute for identification. Likely, this was just the first place the plant was collected and not the invasion start point. Little is known about how or why it got there, but the plant still grows on the creek bank. Perhaps there was a packing house there and the plant was used as packing material or maybe it floated downstream. Since then, *Microstegium* now occurs in 25 states, Puerto Rico and the District of Columbia. It continues to spread (Mehrhoff, 2010).

- **The full scientific name is *Microstegium vimineum* (Trin.) A. Camus, in the Andropogoneae Tribe, Poaceae.** Taxonomic synonyms are: *Eulalia viminea* (Trin.) Ktze., *Andropogon vimineum* Trin., *Pollinia inberbie* Nees, *Eulalia viminea* var. *variabilis* Ktze., *Microstegium vimineum* var. *inberbe* (Nees) Honda (*inberbe* variety is not recognized anymore). It is also known by the common names: Japanese stilt-grass, Nepalese browntop, Eulalia, Chinese packing grass, and *Ashiboso* in Japan (Mehrhoff, 2010).

- **Watch for new plants on the invasion front.** *Microstegium* has yet to reach its maximum distribution. Currently, the most important areas to watch for *Microstegium* are at the edge of the invasion front, although the methods of spread do not suggest we should only search for new invasions in areas adjacent to its existing range. This plant has many vectors for dispersal, the most important of which are people and water, and it may jump spatial gaps. See the county distribution map for known locations of invasion (Figure 1) (Ielmini, 2010; Mehrhoff, 2010).

- **Report new findings.** New findings of *Microstegium* can be reported at EDDMapS (http://www.eddmaps.org). You can also view updated distribution maps at this site (Evans, 2010b).

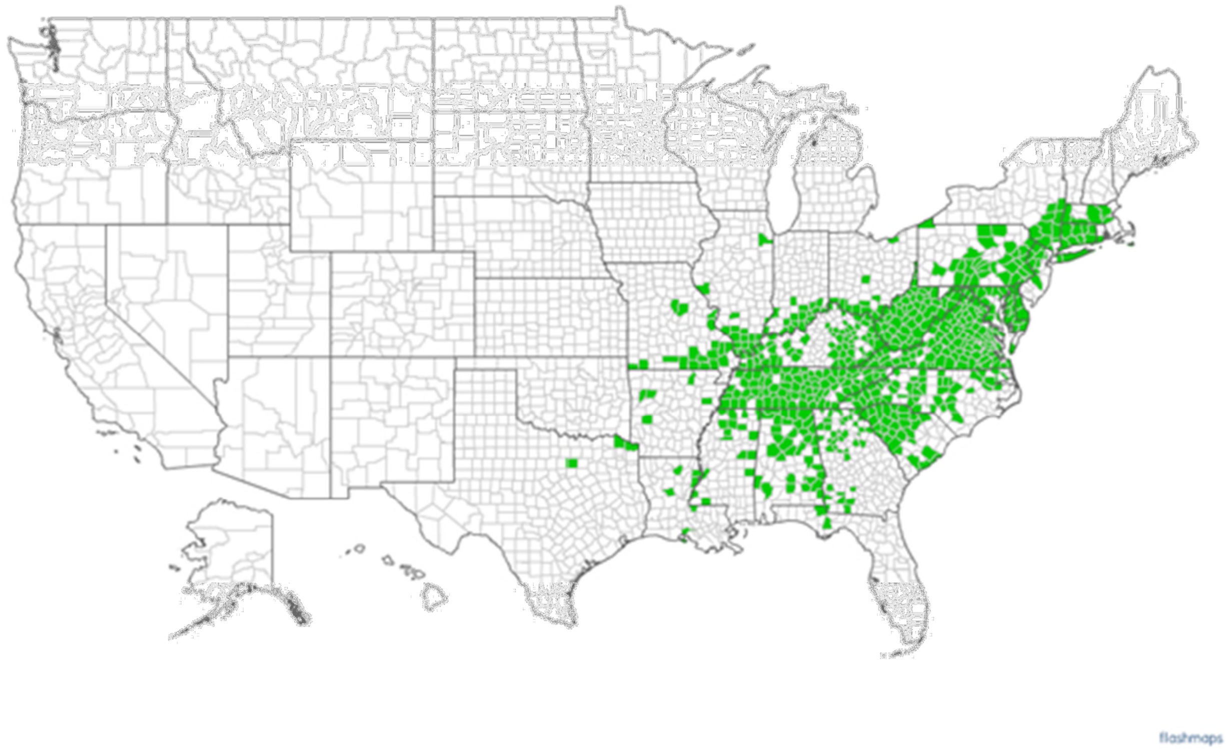

Figure 1. The current distribution of *Microstegium vimineum* in the United States by county (EDDMapS, 2011).

- **Plants and seeds may be carried by many different vectors.** Some human associated vectors are: clothing, boot or shoe treads, pets, horse hooves, car and bicycle tires, mowing equipment, canoes, logging or agricultural machinery, construction crews, road graders, soil or mulch transport, and the creation of fire breaks. (Evans, 2010a; Mehrhoff, 2010). Propagules may also move through natural abiotic and biotic means, such as water and wildlife. Flood events seem to greatly facilitate spread. Some animal vectors, deer for example, have large home ranges. In a study from the Connecticut Agricultural Experiment Station (Williams *et al.*, 2008), the authors took 566 samples of deer pellets from 2002-2005 and conducted a germination study, finding 40 species of exotic plants, including *Microstegium*. Water flow also moves the seeds, which are light enough to not break the water surface tension (Mehrhoff, 2010).

- **Correct identification is important.** *Microstegium* is commonly confused with the native grass, *Leersia virginica*. The two species often grow together at the same site. There are several distinguishing characteristics. *Microstegium* generally has a white midrib in the leaf center. However, this may not always be present, especially at the seedling stage; and *Leersia* has also been observed to have a white midrib on occasion. A better character is belowground growth; *Leersia* is a perennial and has underground rhizomes with scales, while *Microstegium* is an annual with a fibrous root system. No perennial form of *Microstegium* exists, although a paper was published incorrectly suggesting so (Ehrenfeld, 1999), where it is likely that *Leersia* was misidentified as *Microstegium* (Mehrhoff, 2000). Another good character to look for is contrasting nodes – *Microstegium*'s are glabrous, while *Leersia* has hairy nodes. *Leersia* leaves are usually longer than the leaves of *Microstegium* (about 15cm, compared to 4-8cm for *Microstegium*). The fruits are much different; often there are small awns on *Microstegium* fruits, and *Microstegium* has a more compact inflorescence than *Leersi*a. Additionally, *Microstegium* has hairs at the sheath summit and along leaf margins, glumes present at spikelet base, yellow or pale purple color of stands in the fall (*Leersia* is yellow, straw-colored), and flower initiation after mid-September (*Leersia* flowers a month earlier or more). It is an environmental disservice and a waste of effort to eradicate native *Leersia* (Mehrhoff, 2010).

Impacts and ecology

Population level

Niche limitation

- **The presence of *Microstegium* in the environment does not mean that the invaded location satisfies niche requirements.** Niche is defined as a space where all the resources a species needs for survival and reproduction are available. A species may be present at a location and still lack sufficient resources to reproduce; and therefore, may be found outside its reproductive niche. The presence of a species outside of its reproductive niche may be maintained by source-sink population dynamics. While it seems there are few limits to *Microstegium* invasion, there are some suggestions of niche limitation in the form of leaf litter depth, shading, dispersal limitation, and soil moisture availability (Warren, 2010; Warren *et al.*, 2011).

- **At the regional scale of study, *Microstegium* may be limited by distance to waterways.** Niche requirements at the regional scale were tested by establishing GPS transects (0.5 – 2 km each) in select locations, across a 100 km regional gradient spanning from the Southern Appalachians of North Carolina to the Southern Piedmont in Georgia, at 10 km intervals using a total of 221 $4m^2$ plots in forested and unforested habitats. Data taken were: *Microstegium* presence and percent cover, elevation, aspect, slope, distance to roads or waterways, canopy cover, and temperature. Classification tree (CART) models were used to examine relationships between *Microstegium* and environmental variables. The factor with the highest association to *Microstegium* landscape cover was distance to waterway, with distance to roads as the second most relevant, supporting the inference that there may be some limitations in low levels of available soil moisture. However, at the regional scale, it is unclear whether this is a result of dispersal or a true niche requirement (Warren, 2010).

- **At the local scale, invaded plots had less leaf litter, more moisture, and higher pH, and plants exposed to higher levels of temperature and light had greater reproductive output, suggesting possible niche requirements.** To examine factors at a smaller scale, paired plots, invaded and uninvaded (n=72) were established at forest edges, across the invasion line of *Microstegium* patches. Environmental factors measured were: soil moisture availability, light levels, temperature, percentage of leaf litter, percentage of native herbaceous plant cover, pH, and percentage of clay. *Microstegium* response variables were percent cover, biomass, and mass of reproductive output. Relationships were tested using linear mixed models (LMMs) with location as a random effect and environmental variables as fixed effects. The assumption was that if invasions were a result of random chance, there would be no difference between invaded and uninvaded plots. The results showed some differences which may be interpreted as niche requirements or limitations. *Microstegium* germination rates were lower with increased leaf litter. *Microstegium* biomass increased as percent cover of other herbaceous plants increased, indicating that optimal conditions for other herbaceous plants also support growth of *Microstegium*. Reproductive output was much greater with high light availability, suggesting light availability may be an important niche requirement. The association of *Microstegium* with higher pH is likely a result of *Microstegium* invasion rather than a pre-existing factor supporting site invasibility (Warren, 2010).

Source-sink population dynamics

- **Based upon the documentation of differential performance between edge and interior populations, source-sink population dynamics may be a strong factor influencing invasion.** Not all sites where *Microstegium* is present have equal ability to support growth and reproduction. Studies have shown that the highest levels of performance are associated with resource levels found in forest edges, such as roadsides, and waterways. For example, *Microstegium* establishes best with shallow leaf litter, and reproduces best with high temperature and light levels; and water acts as a dispersal vector. Populations in edge environments may act as a source of seed, which allow populations in interior reproductive sinks to persist. *Microstegium* is found in various edge habitats, while interior populations seem more often to be outliers (Warren, 2010).

Resource requirements

- ***Microstegium* establishes in forest interiors with high native herbaceous plant richness and high percent cover of moss.** Percent cover of *Microstegium* across West Virginia transects was similar in all $1m^2$ plots in which plants were present indicating similar establishment in all sites. Across all sites for two of the three years surveyed, there was an increased likelihood of finding *Microstegium* in sites with high native herbaceous plant richness. This association suggests that conditions which promote the richness of native plants are also the most suitable for *Microstegium* establishment. Tree richness did not follow the same pattern. This positive correlation of *Microstegium* occurrence with increasing native plant richness is also supported by a New Jersey study in the Piedmont Region at the site of the Buell-Small Succession Study; invasion reached plots with the greatest species richness first, although following years saw the spread of invasion to all plots (Meiners, 2010). Also, *Microstegium* was found in areas with the highest percent cover of moss in two out of three West Virginia sites, where the atypical site was the most mesic; percent cover of moss correlates with soil moisture availability (Huebner, 2010).

- **Canopy openness and litter depth may also affect the percent cover of *Microstegium*.** During 2006, the driest year of the West Virginia study, there was greater occurrence of *Microstegium* in plots with the highest percentage of canopy opening in two of the three sites surveyed. The atypical site had the highest canopy openness of the three, and the factor most associated with *Microstegium* presence for this site was litter depth. Areas with the lowest litter depth had more *Microstegium* (Huebner, 2010).

- ***Microstegium* plants grow taller in low light treatments.** At five sites in West Virginia, areas were fenced and various densities of small trees removed to increase light levels in the forest understory. *Microstegium* was introduced (and removed before seed production) within three light treatments: high light (12% of full sun, 240 µmol/m^2/s), medium light (8% of full sun, 160 µmol/m^2/s), low light (4% of full sun, 80 µmol/m^2/s), and control treatment (2% of full sun, 40 µmol/m^2/s). Plants in the low light treatment had greatest stem height (Huebner, 2010). This height difference between sun and shade plants represents a plastic response to light; and therefore, biomass measurements are also important for comparisons (Warren, 2010). Greater thatch height may increase fire intensity of prescribed burns (Flory, 2010).

- ***Microstegium* seedling recruitment in uninvaded plots increased with experimental disturbance, prescribed fire, and flooding.** Niche requirements for the seedling stage of *Microstegium* were tested in select locations, across a 100 km regional gradient spanning from the Southern Appalachians of North Carolina to the Southern Piedmont in Georgia, using experimental disturbance. Disturbances were leaf litter and plant biomass removal from paired invaded and uninvaded plots in summer 2009 and winter 2010, and additionally, prescribed burns and flooding occurred and were incorporated into the experiment. Recruitment was quantified in spring 2010 and analyzed using a general linear mixed model (GLMM). Seedling recruitment was higher in invaded plots, disregarding disturbance. The survey of uninvaded plots showed that disturbance facilitates significantly greater seedling recruitment through leaf litter removal. Disturbance in invaded plots did not cause further increase in recruitment. Flooding and increases in soil moisture also promoted seedling recruitment, as overland water flow re-distributed leaf litter (Warren, 2010).

Reproduction and seed dispersal

- **The numbers and types of flowers are different for roadside and interior populations of *Microstegium*.** While this has already been noted (Cheplick, 2007; Huebner, 2007; Kuoh, 2003), roadside and interior populations vary by the quantity of cleistogamous inflorescences per plant stem. Cleistogamous florets are closed, located at stem internodes, while chasmogamous florets are wind-pollinated and open, located at terminal racemes. Interior and roadside populations in West Virginia, from the Allegheny Plateau to Ridge and Valley Province, were compared by establishing sixteen 50m transects across three sites from roadside into the forest, setting up 1m^2 plots every 5m. There was a regional gradient which varied in moisture (average 79 cm – 160 cm annual precipitation) and temperature (25 C – 30 C). Roadside light availability was approximately 200-300 µmol/m^2/s, while interior light levels were 20-40 µmol/m^2/s. Generally, there were more inflorescences in the roadside populations, likely attributable to larger plant size. Number of inflorescences per stem were quantified and categorized into one of four types: chasmogamous, partial chasmogamous, partial + chasmogamous, and cleistogamous. Inflorescences with mostly closed and some open florets were labeled partially chasmogamous; the partial + chasmogamous category combines chasmogamous and partially chasmogamous inflorescence counts. The ratio of partial + chasmogamous inflorescences to cleistogamous inflorescences was greater for the interior populations, although more chasmogamous inflorescences were produced in edge populations (Huebner, 2010).

- **Floret size, seed viability, and fitness vary across the roadside to interior gradient.** Of the two floret types, chasmogamous and cleistogamous, the chasmogamous florets were greater in size. Sizes of florets found in the interior populations were intermediate between roadside chasmogamous and cleistogamous sizes. Floret mass (g/100 florets) was also the highest for the chasmogamous type. Seed mass was lower for all floret types in the driest sites, although this had no effect on seed viability, which was tested for all sites and floret types using tetrazolium and germination tests. Germination rates were highly variable in seed under a year old, but by three years, seed from chasmogamous florets had the greatest probability of remaining viable. Even at two years, viability of seed stored in refrigerated conditions had dropped to 50%. Less viability would be expected in natural conditions for the same time periods due to the activity of predators and fungal pathogens. There was also a non-significant trend for seed from chasmogamous florets in drier sites to remain viable for longer time periods than seed from more mesic conditions. These data suggest that following a three year period of controlling *Microstegium* reproduction, viability may be lost in cleistogamous roadside and forest interior seed. Therefore, management efforts may focus on controlling seed produced from chasmogamous florets (Huebner, 2010).

- **Documented rate of spread is more rapid in mesic compared with dry conditions, especially when associated with flooding, and in areas with low slope or timber harvest.** Seed is usually deposited in close proximity to the mother plant, in the absence of a dispersal vector. Dispersal was studied using a reaction-diffusion model for 369 $1m^2$ plots located across West Virginia transects at three sites over three years. Seeds were collected using sticky traps, placed every 5m along transects. The distribution curve was leptokurtic, indicating a narrow spread distance. For all sites, there was less *Microstegium* seed with movement along the transect into the forest interior. Transects through sites with the most mesic conditions had the greatest seed dispersal distances and colonization rates, especially in the driest study year. The spread rate at the driest site was estimated to be 0.15m per year, which would take up to 60 years to reach full site saturation, while the most mesic site had a spread rate of 0.5m per year, giving an estimated 12 year saturation timeline (Huebner, 2010). In another study, dispersal distance of *Microstegium* seed was tested using fluorescent paint to mark seeds before dehiscence. In February after seeds had dispersed, the ground was searched surrounding plots using a UV light to illuminate the fluorescent paint. Seeds had traveled approximately 1.5m in the site with the lowest slope. The greatest dispersal distance was 8m, likely due to the flow of storm water along a ditch from the roadside into the forest (Warren, 2010). In a study from Southern Indiana, one site with natural flood disturbance had a 474% increase in the cover of *Microstegium* within a period of two years. While this was the greatest documented rate of spread, generally naturally disturbed and undisturbed sites had lower rates of spread than sites of timber harvest. *Microstegium* cover increased by 388% within two years in one site of timber harvest (Shelton, 2010).

Community and ecosystem level

Effects on the microbial community

- **Studies have shown conflicting results for effects of *Microstegium* on microbial biomass, community composition and function, carbon dynamics, and Nitrogen cycling** (Fraterrigo, 2010; Kourtev *et al.*, 2003; Wright, 2010). Some differences may be a result in various methodologies, while others are likely to be a result of plant response to local environmental conditions.

- ***Microstegium* may increase microbial biomass and may cause microbes to lose denitrification ability when given only DI water, instead of leaf-leachate.** A greenhouse study was conducted using pots containing plantings of two native species, *Carex crinita* and *Eupatorium fistulosum*, *Microstegium*, and field soil only. Leaf-leachate was produced from dried leaves of each species and used to incubate soil in pot treatments. Substrate Induced Respiration (SIR) was used to look at results on microbial biomass. Denitrification potential was also examined. Leaf-leachate had less of an effect than the presence of live plants. The presence of *Microstegium* caused an increase in microbial biomass as compared to control, *C. crinita*, and *E. fistulosum* treatments. Change in function of microbial community was evident through change in denitrification rate. Soils with *Microstegium* plants lost denitrification ability with only DI water. *Carex crinita* leachate suppressed denitrification in pots planted with *C. crinita*, but *Microstegium* soil communities showed enhanced denitrification with *C. crinita* leachate (Fraterrigo, 2010; Kourtev *et al.*, 2003; Wright, 2010).

- ***Microstegium* may change soil microbial community composition and function** (Kourtev *et al.*, 2002). An example of this is an increase in arbuscular mycorrhizal fungi (AMF) relative to other fungal species. AMF are plant mutualists; they colonize plant roots and send out hyphae which facilitate exchange of nitrogen and phosphorous for plant-produced carbon. There may also be an increase in saprotrophic fungal species and an "increase in N-related enzymes". Other studies have shown a decrease in microbial biomass, reduction in stocks of carbon, and greater microbial community activity despite biomass reduction (Fraterrigo, 2010; Strickland *et al.*, 2009).

- **Other ecosystem impacts may be explained through interaction between plants and the microbial community** (DeMeester & Richter, 2010; Ehrenfeld *et al.*, 2001; Fraterrigo, 2010). Examples are increased soil pH, decreased litter decomposition rates, slower release of N due to microbial immobilization during decomposition, increased nitrate in aerobic soils, increased ammonium in anaerobic soils, and increased nitrification.

Nitrogen cycling

- **The forest understory community shows increased N uptake in invaded areas, although allocation patterns change with invasion.** In contrast to uninvaded areas, native plants experiencing invasion allocate more N to aboveground tissue than belowground. Also, native plant roots show greater sequestration of N (Fraterrigo, 2010). These patterns were determined using a ^{15}N isotope tracer experiments in a mixed hardwood forest at Whitehall Experimental Forest, Georgia. There were three tracer treatments (^{15}N-^{13}C-glycine, ^{15}N -$NaNO_3$, and ^{15}N -NH_4Cl), and measurements taken were percent N uptake in relation to ^{15}N addition, proportion of N uptake "relative to total N pool", and "ratio of microbial uptake to plant uptake to get at the idea of competition". In the percentage and proportion of ^{15}N uptake, plants showed greater uptake of N in invaded plots (percentage: $F_{1,36}$=16.41, p=0.001; proportion: $F_{1,36}$=8.04, p=0.009). The highest percentage of ^{15}N was stored in aboveground *Microstegium* tissue, while most of the N in native species was stored belowground whether or not plots were invaded (Fraterrigo, 2010).

- ***Microstegium* has a high Nitrogen use efficiency (NUE).** NUE is determined by dividing plant biomass by the amount of N held in tissue (g/gN). "On a per unit basis for N, *Microstegium* can produce a lot more biomass" (Fraterrigo, 2010). The NUE of native forbs, sedges and grasses is less than half that of *Microstegium* (Lee 2010). *Microstegium*'s high NUE may partially explain the invasive's ability to outcompete native plants; it may not be a better competitor for N, just more efficient at assimilating it, leading to a high C:N ratio in *Microstegium* thatch. The microbial community may become N limited (Fraterrigo, 2010).

- ***Microstegium* may decrease microbial biomass, with fewer microbes sequestering the same amount of N as those in uninvaded sites, potentially altering carbon dynamics – C:N ratio.** Contrary to greenhouse studies indicating an increase in microbial biomass (Wright 2010), Whitehall Experimental Forest sites which were invaded by *Microstegium* showed a decrease in microbial abundance ($F_{1,36}=17.58$, $p=0.006$); however, microbes sequestered the same amount of N as compared to those in uninvaded sites with greater microbial biomass ($F_{1,36}=1.01$, $p=0.33$). These data seem to indicate a more active microbial community in invaded areas. This may influence plant uptake of N, increasing competition between microbes and plants for N. The microbial community may become N limited in areas with large amounts of decaying *Microstegium* thatch. *Microstegium* litter has a high C:N ratio (DeMeester & Richter, 2010), which may explain a shift to greater numbers of AMF and saprotrophic fungi, species more efficient at extracting N from tissues with high C:N ratios (Fraterrigo, 2010; Kourtev *et al.*, 2002; Kourtev *et al.*, 2003). This microbial activity may make N more available for native plants or *Microstegium*. Plants in invaded sites take up more N; the ratio of microbial biomass N: plant N is likely to be lower in non-invaded sites ($F_{1,36}=14.03$, $p<0.001$) (Fraterrigo, 2010).

- **Nitrogen content of *Microstegium* tissue is different from native plants and may affect N cycling.** *Microstegium* has lower foliar concentrations of N as compared to native plants. Lower N content may cause slower decomposition of plant biomass. Studies suggest that N may not be available as quickly when *Microstegium* litter breaks down compared to native plants, potentially due to sequestration by microbes (DeMeester & Richter, 2010; DeMeester, 2009; Fraterrigo, 2010).

- ***Microstegium* shows a preference for inorganic forms of N.** N preference was tested in a greenhouse experiment. Soil from a common garden experiment in which *Microstegium* was grown was taken and mixed with sand in a 2:1 mixture and placed in gallon pots. Three seeding treatments were used: *Microstegium* monoculture, *Microstegium* and native plant mixture, and native plants only. Native plants were 2 forb species, 2 grass species, and 2 sedge species. Nutrient treatments consisted of a control, nitrate, ammonium, and ammonium plus a nitrification inhibitor (Nitropyrene, which inhibits the growth of nitrifying bacteria). Treatments were replicated 15 times, controls 5 times. *Microstegium* produced more biomass in the ammonium treatment ($p=0.0506$) and less biomass in the ammonium plus nitrification inhibitor substrate, while growth of native plants was not different in the presence of the nitrification inhibitor (Lee 2010). *Microstegium* also produced less biomass when the dominant form of N is nitrate. Less biomass was also produced when competing with native plants, but there were no difference in

Microstegium biomass in the nitrate and ammonium treatments in mixtures. Native plants alone showed no preference between nitrate and ammonium; but when mixed with *Microstegium*, natives produced more biomass in the nitrate treatment, perhaps indicating lower competitive ability of *Microstegium* for nitrate (Lee, 2010). Whitehall Experimental Forest treatments using ^{15}N isotope tracers also suggested *Microstegium* did not show a preference between nitrate or ammonium, but took up less glycine ($F_{2,36}$=8.38, p=0.007). However, microbes showed an ammonium preference at both 50 hours and 8 days after ^{15}N isotope labeling ($F_{2,36}$=7.45, p=0.003) (Fraterrigo, 2010).

- ***Microstegium* promotes nitrification.** In a monoculture, *Microstegium* was more productive when provided with nitrate than ammonium (Lee, 2010). Studies have shown higher levels of nitrates and higher nitrification rates in areas invaded by *Microstegium* (Ehrenfeld *et al.*, 2001; Kourtev *et al.*, 1998). In a greenhouse comparison, "*Microstegium*-conditioned" soil had higher rates of nitrification than one other invasive species and one native species often found growing at the same sites as *Microstegium* (Lee, 2010). Over the course of a growing season, nitrification rates in forest understory plots invaded by *Microstegium* were 124% greater than control plots (p=0.097), and common garden plots seeded with *Microstegium* had 64% greater nitrification rates than plots seeded with native perennials (p=0.001) (Lee, 2010). Higher nitrification rates were seen in soils with *Microstegium* monocultures in greenhouse, common garden, and natural invasion studies, and there was also a trend of increasing nitrification with increasing *Microstegium* biomass in mixtures (p=0.0738), although a critical mass may be required before nitrification effects are evident (Lee, 2010).

Secondary plant compounds and allelopathy

- **The effects of *Microstegium* on ecosystems may be attributed to properties of secondary compounds** (Meiners, 2010; Wright, 2010). Plant secondary compounds are any biochemicals synthesized that do not directly contribute to photosynthesis or respiration, potentially affecting herbivory, the soil community, and tree regeneration (Wright, 2010).

- ***Microstegium* leaf-leachate has allelopathic properties.** Allelopathic potential (general inhibitory effects on growth of other plants) of *Microstegium* was tested on radish seeds using tea made from known amounts of plant tissue. Germination decreases with increasing concentration of extract. Plants with previously known allelopathic effects, *Alliara petiolata* (garlic mustard), *Ailanthus altissima* (tree of heaven), and *Solidago* spp. (goldenrod), had similar effects on germination, although *Microstegium* was less toxic than *Solidago* (Meiners, 2010; Pisula & Meiners, 2010).

- **Allelopathy of *Microstegium* may reduce density of some species of tree seedlings.** Studies have shown decreased tree seedling densities in invaded plots (DeMeester & Richter, 2010; Flory & Clay, 2009), though tree species begin to emerge again following *Microstegium* removal. The mechanisms behind the suggested inhibition then documented re-emergence may be difficult to discern, possibly related to increased light levels, exposure of mineral soils, or removal of chemical inhibition due to plant secondary compounds. Allelopathy of *Microstegium* leaf-leachate, was tested on the germination of *Liquidambar styraciflua* (sweetgum), *Ailanthus altissima* (tree of heaven), and *Acer negundo* (boxelder). Treated seeds of *Ailanthus altissima* showed decreased germination, while germination of *Liquidambar styraciflua* increased. There was no significant effect on *Acer negundo* (Wright, 2010).

- **Differential effects on tree species may inhibit succession and cause a shift in forest community composition over time** (Flory, 2010). The effect of invasion by *Microstegium* on different tree life history stages was studied in a long-term experiment in Indiana. *Microstegium* was randomly applied to a subset of plots in a blocked design where either tree saplings were planted or tree seeds sown. Seeds were planted to simulate old-field succession, while planted saplings simulated later successional stages. Some tree saplings showed higher mortality in invaded plots, and recruitment was more than four times greater than in invaded plots. Greater impact was observed for early successional simulations, particularly for small seeded tree species. Invasion had no significant effect on large seeded tree species [oaks or hickories], although there was a trend for decreased survival of *Quercus palustris* (pin oak), *Quercus alba* (white oak), and *Quercus macrocarpa* (bur oak). The number of small seeded tree species, *Liquidambar styraciflua* (sweetgum), *Liriodendron tulipifera* (tulip poplar), and *Fraxinus pennsylvanica* (green ash), decreased in invaded plots (Flory, 2010). This effect was dramatic for *Liquidambar styraciflua*, in seeming contrast to the results of Wright (Wright, 2010), where *Microstegium* leaf-leachate increased germination of this species. Additionally, a survey of naturally invaded areas found reduced regeneration for *Acer negundo* (boxelder), *Acer rubrum* (red maple), and *Lindera benoin* (spicebush), while there was no effect on *Cornus sericea* (red osier dogwood) (Flory & Clay, 2010).

Herbivory

- **Secondary compounds are insufficient to prevent herbivory or infection by the fungal pathogen *Bipolaris* sp., discrediting the enemy release hypothesis** (Kleczewski & Flory, 2010; Wright, 2010). Invading plants with unique secondary compounds may have specialist herbivores in their native habitats that have adapted the ability to feed on them. Population explosions of some exotic invaders may be explained by this absence of specialist herbivores (enemy release). If *Microstegium* produces secondary compounds, it is possible the chemicals are not strong enough to deter herbivory or herbivores are adapting to digest them (Wright, 2010). In a survey of 10 native species along with *Microstegium* in Durham, North Carolina, *Microstegium* showed lower percent damage from herbivory compared to other native plants; however, herbivory rates were comparable to other native grasses, *Panicum virgatum* (switchgrass) and *Uniola latifolia* (river oats). Low herbivory rates for surveyed grasses are likely a result of tissue quality and silica content, rather than presence of plant secondary compounds (Wright, 2010). As a C4 grass, *Microstegium* has a unique carbon signature. Carbon from *Microstegium* can be followed through ecological pathways by looking at this ratio of ^{12}C:^{13}C(Wright, 2010). One study showed that 7 of 8 invertebrates surveyed, in the orders Orthoptera and Hemiptera, took greater than 35% of their carbon from *Microstegium* (Bradford *et al.*, 2010). A new fungal pathogen, *Bipolaris* sp., was isolated from *Microstegium* tissue in Indiana. *Bipolaris* causes lesions on plant leaves, wilting, possible mortality, and reductions in fitness, decreasing production of seed heads by 40 % (Kleczewski & Flory, 2010).

- **Herbivory was lower under low light availability, representing a potential cascading ecological effect.** In light manipulation treatments, induced by small-scale disturbance, plant growth increased rapidly when light levels increased. Herbivory, in the form of stem removal, was greater in these plots experiencing a flush of new growth, perhaps because of the additional cover provided for the protection herbivores against predators. Two likely herbivores were chipmunks and snails (Huebner, 2010).

Community and ecosystem losses

- ***Microstegium* invasion poses a serious threat to ecosystems through loss of diversity of native plants and arthropods, changes to forest succession, nutrient dynamics, and decomposition rates, presence of disease vectors, and alteration of fire behavior and carbon storage** (Flory, 2010). Invasive species in general cause 50 – 85 % of the decline in biodiversity. Five percent of the world economy, over 137 billion dollars in the U.S. each year, is lost due to the impact of invasive species. The loss of cultural resources and quality of life is incalculable. Besides habitat loss (impacting 85 % of endangered species), invasives are the primary factor endangering species (49 %), then pollution (24 %), overexploitation (17 %), and disease (3 %) (Ielmini, 2010; Wilcove *et al.*, 1998).

- ***Microstegium* changes plant community richness (number of species), plant diversity, and overall groundcover, out-competing other species** (Meiners, 2010). Experimental plots were located in the Piedmont region of New Jersey, and plots encompassed $1m^2$ of young forest habitat. The plot with the longest history of invasion (6 years) had 70 % *Microstegium* cover, while other, later invasions are quickly expanding at 20 – 40 % cover. High levels of invasion caused the loss of two species, on average, while low levels of invasion caused the loss of approximately one species in experimental plots, when comparing invaded to uninvaded plots. The loss of natives represents a significant impact at such a small scale of measurement. Plant diversity follows the same patterns (Meiners, 2010). A long-term Indiana study showed similar decreases in native plant diversity and productivity, where *Microstegium* was randomly applied to a subset of plots after establishment of 9 tree species and 12 herbaceous species. After three years, native biomass was still lower in invaded plots, with up to 64 % reduction. Diversity was 38 % lower and richness 43 % lower in invaded plots. Community divergence in invaded vs. uninvaded plots was shown using nonmetric multidimensional scaling ordination (Flory, 2010; Flory & Clay, 2009).

- ***Microstegium* invasion has cascading ecological effects on the arthropod community.** The arthropod community was sampled in invaded and uninvaded plots on two dates, June and September. Invaded plots showed a 19 % decrease in arthropod richness and a 39 % decrease in arthropod abundance. Abundance and diversity of carnivores and herbivores was reduced, although the effect was much larger on carnivores (Flory, 2010; Simao *et al.*, 2010).

Resistance of native community to invasion

- **Native plant communities have little capacity to resist invasion, although there are two documented cases of naturally failed invasions over several years at one site.** A New Jersey survey of invasion at the Buell-Small Succession Study found that although plots with the greatest native species richness are invaded first, invasion eventually reaches all plots, irrespective of richness. Once introduced at a location, persistence is likely. However, *Microstegium* colonized a few old-field plots in the early 1980's and again in 1987 and then disappeared. The factors leading to invasion failure are unclear, but at the time, plots were dominated by goldenrod and shrubs. The forest was in a degraded state, which should have increased the likelihood of successful invasion. In later years, *Microstegium* became established within the forest in a separate invasion event and is currently able to compete with goldenrod in old-field habitats (Meiners, 2010).

Landscape level

Predictive models

- **It may be possible to develop predictive models useful in assisting land managers in predicting invasion and spread of *Microstegium*.** The area of interest is generally individual properties, approximately 1 – 1000 km. Developing models for this scale requires integration of models at a large, geographic scale, where the area of interest is species distribution models or environmental niche models (Phillips *et al.*, 2006), and small scale models at the resolution of meters, where the interest is local patch dynamics, looking at how far a species will spread within a year (Rauschert *et al.*, 2010; Shelton, 2010). A model at an intermediate scale would help land managers maximize limited resources and answer questions such as: "Where should [land managers] focus search efforts for new invaders?", "Which existing patches should be priorities for eradication?", "Which [patches] will have the greatest impact on population spread?" (Shelton, 2010).

- **Patterns of *Microstegium* occurrence vary with local environmental variables such as slope and light availability, distance from dispersal corridors (roads and streams), and distance from disturbances in the form of tree harvests.** Establishment of a correlation between presence of *Microstegium* and site characteristics was necessary to form the basis for developing a predictive model. A survey of *Microstegium* invasion occurred in Southern Indiana, where *Microstegium* had been observed since the early 1970's. Local sites were assessed by establishing a perimeter and searching for any occurrence within the area in sites with undisturbed forest, storm-damaged forest, and harvested forest, focusing on roads, trails, and streams. Data were taken on patches, including location (GPS coordinates), patch size, density, height, and light availability (sky-view hemispherical photos). Environmental predictors were slope (flat, shallow, moderate, steep), aspect (flat, NE, SE, SW, NW), light availability (deep shade, shaded, part sun, sunny), and distance to roads, trails, streams, and previous year's invasion boundary (6, 30.5, 97.5, and 1005.8 m); and measurements were extrapolated from photographs using a Kriging algorithm (Shelton 2010).

- ***Microstegium* is most common on flat slopes, in partial sun, either near or very far from streams, close to roads, and / or close to timber harvests.** If *Microstegium* had been randomly distributed, the observed occurrence would be proportional to the number of sites surveyed in each category for each environmental variable of interest. However, when the expected (all sites surveyed) distribution is subtracted from the observed (sites with *Microstegium*) distribution, the percent difference indicates that *Microstegium* is more common on flat slopes (29%) than shallow (2%), moderate (-19%), or steep (-11%) slopes. *Microstegium* was more abundant in partial sun (30%), compared to sunny (2%), deep shade (-9%), or shaded (-20%) environments. Although sunny sites had a positive percent difference, *Microstegium* plants seemed to suffer from lack of moisture in these locations. Correlation with distance to streams was bimodal with two explanatory variables. Water is a dispersal mechanism, and *Microstegium* was found at distances of 6 m (5%) and 30.5 m (6%) from streams, while at a distance of 97.5 m, the percent difference was negative (-20%). At 1005.8 m (10%) from streams, occurrence of *Microstegium* may be explained by the movement of trucks on ridge tops as a vector. *Microstegium* occurred more often close to roads, 6 m (5%), 30.5 m (11%), 97.5 m (2%), and 1005.8 m (-18%), and close to timber harvests, 6 m (17%), 30.5 m (-4%), 97.5 m (-6%), and 1005.8 m (-6%). Values reported are approximations based on presented values from graphs from one geographical location, a 15-20 year old log yard and some skid trails with a small invasion. The site was surveyed before a scheduled 2008 harvest and again after. Within one year of establishment of a new log yard, there was 100% *Microstegium* cover, and *Microstegium* was present in every location where there was vehicle movement (Shelton, 2010).

- **Once a predictive model for *Microstegium* invasion is developed, it will be publicly available.** Using the survey data collected from Southern Indiana sites, Bayesian statistical methods were used to assign probabilities of occurrence of *Microstegium* to all categories of environmental variables, exporting the GIS data to Netica Bayesian analysis software. The environmental variables are used to calculate probability of *Microstegium* occurrence for each map coordinate. The generated probabilities are then projected onto a map, giving the likelihood of *Microstegium* presence at each coordinate. Six out of 10 sites were used to create the model; the accuracy of the model will be tested using the other 4. The final model will contain only those factors deemed most predictive. Since many other invasive species are dispersed by humans and water, the model may be extended to other plants (Shelton, 2010).

Management

- **The concept of Early Detection Rapid Response (EDRR) is critical in controlling *Microstegium* and other invasive species.** Invasions typically follow a sigmoidal or J-shaped curve. At first appearance, there are only a few individuals. Then, over time, the population increases to the point of public awareness, beginning the reactive stage of invasion, where control becomes an issue. Early detection represents a paradigm change. The species is identified and control occurs immediately. EDRR costs much less, prevents ecological damage, and protects against the loss of ecosystem services. However, it is important for responses to be well planned, strategic, and rapid (Ielmini, 2010; Mehrhoff, 2010). The ability to implement EDRR must be increased, requiring an investment at all management scales, from local to national (Ielmini, 2010). Seven important EDRR questions land managers may ask themselves are: "Is this species going to get to my property? Where on the property will it first show up? Will it become naturalized? Who will discover it? Will they report it to me? Will we identify it correctly? Will it become invasive on my property?" (Mehrhoff, 2010).

- **There are four key elements to management programs for *Microstegium* and other invasive species.** These are: prevention, EDRR, control and management, rehabilitation and restoration. Management programs benefit by focusing on prevention first. Once invasion occurs, EDRR must then be used to control populations and prohibit spread to other areas. After the invasion has been managed, the ecosystem must be restored in a way that promotes resilience to future invasion (Ielmini, 2010).

- **At the present scale of infestation, herbicides are a necessary management tool; however, a management plan needs to be in place before using herbicides.** Take the anecdotal example of two natural areas in New Jersey with different management approaches: Great Swamp National Fish and Wildlife Refuge (GSNFWR) and the area of Jockey Hollow, Morristown National Historic Park. GSNFWR does not manage with herbicides, and there are areas with heavy infestations within the refuge. However, other GSNFWR areas have little *Microstegium*, and it is managed through hunting to control the local deer herd and manage the forest overstory. This is in contrast to Jockey Hollow, an area where the salamander, *Pseudotriton ruber*, once existed in the streams and wetlands, now covered in *Microstegium*. A search for *Pseudotriton* in the summer of 2010 was unsuccessful. If extirpated, it may not be because of *Microstegium*, but if herbicide had been used, it would have impacted salamander populations. Development of a management plan is critical. Maintenance and preservation of biological diversity is one of the most important reasons to control the spread of invasive species (Mehrhoff, 2010).

- **Controlling deer populations may assist in combating *Microstegium* invasion.** Deer may be vectors for long-distance dispersal of *Microstegium* and other exotic invaders (Mehrhoff, 2010; Williams *et al.*, 2008). Additionally, deer may selectively browse the shrub layer, facilitating the spread of *Microstegium* (Schramm & Ehrenfeld, 2010).

- **The spread of *Microstegium* along roads as a result of vehicle traffic may require management plans.** In recent years, there has been a 30-40% reduction in the number of US roads. Upon decommission, roadways may require management and restoration to prevent and control the spread of invasive species. New road construction and maintenance may also enhance the vulnerability of areas to invasion. In order to bring greater awareness to road maintenance crews, the USDA Forest Service San Dimas Technology and Development Center, National Forest System Invasive Species Program, the US Department of Transportation Federal Highways Administration, the US Department of the Interior Fish and Wildlife Service, and the Pennsylvania Department of Transportation have developed a training video, *Dangerous Travelers: Controlling Invasive Plants Along America's Roadways*, available from the US Forest Service website: http://www.fs.fed.us/invasivespecies/prevention/dangeroustravelers.shtml (Ielmini, 2010).

- **Strategic management of *Microstegium* should focus efforts on controlling edge populations and should take into consideration climate, topography, and age and size of the population.** More seed from chasmogamous flowers is produced in edge populations, and these seed tend to have the longest viability. Forest interior populations produce seed with limited viability. Therefore, interior populations may be more likely to go extinct than edge populations and may rely on re-introduction of propagules from edge populations for persistence. *Microstegium* spreads more slowly in dry conditions, potentially allowing more time to manage these populations (Huebner, 2010).

- **Restoration of habitats invaded by *Microstegium* may occur by removing the invasion with a low concentration of grass-specific herbicide.** Although research shows that *Microstegium* invasion reduces native species richness and prevents forest succession, removal may reverse these impacts. After removal, biomass and diversity of native species increased and native tree seedling emergence increased by more than 120%. Use of a grass-specific herbicide, 0.21 kg a.i. ha of fluazifop-P-butyl, yielded greater increases in the native community than hand weeding or use of a pre-emergent herbicide. These conclusions were drawn from a *Microstegium* removal experiment in Indiana, where the four removal treatments were: no removal (control), hand weeded plots, post-emergent grass-specific herbicide application, and post-emergent grass-specific herbicide with a pre-emergent herbicide. Removal treatments were carried out for two years and replicated in 8 sites. Hand weeding and application of post-emergent herbicide was done in June 2005 and 2006, and pre-emergent herbicide was applied before *Microstegium* germination in April 2007 and 2007. While all treatments reduced *Microstegium* in the study plots, herbicides had a greater impact than hand weeding. There was a 75% return of *Microstegium* in hand weeded plots in the spring following control efforts, and tree seedling recruitment was negatively impacted, possibly due to damage to seedling root systems during removal. Post-emergent herbicides reduced *Microstegium* presence by 97% after two years of treatment, and tree seedling recruitment was highest in the post-emergent herbicide treatment plots. However, when a pre-emergent herbicide was mixed with the post-emergent herbicide, recovery of the native community was impacted with no increase in the level of control (Flory, 2010; Flory & Clay, 2009). While all grass-specific herbicides tested yielded similar results, levels of control for several grass-specific and other herbicides can be found in the literature (Flory, 2010; Judge *et al.*, 2005a, b; Judge *et al.*, 2008). While use of pre-emergent herbicides may negatively impact native community recovery, benefin plus oryzalin, dithiopyr, isoxaben plus trifluralin, oryzalin, oxadiazon, pendimethalin, prodiamine, or trifluran may yield 87 % control or more after 8 weeks (Judge *et al.*, 2005a). Other effective post-emergent herbicides were clethodim, fenoxaprop-P, sethoxydim, glufosinate, and glyphosate, yielding up to 99 % control, while dithiopyr, MSMA, and quinclorac were ineffective (Judge *et al.*, 2005a). Judge *et al.* (2008) also indicated that mowing before seed set may be used as a management option.

- **Preliminary experimental results in Indiana seem to indicate that *Microstegium* invasion may cause increased prescribed fire intensity.** There were greater flame heights and temperatures, and a fire spread to a greater area of land in invaded patches. These Indiana results are potentially more conservative measures than would be seen in other states; in the spring at the time of prescribed burns, *Microstegium* thatch is generally compressed at the ground layer from the winter's snow pack. In regions with less frozen precipitation or during warmer winters, standing, vertical layers of *Microstegium* thatch may further increase fire intensity (Flory, 2010). Effects of *Microstegium* thatch on fire intensity may be similar to those documented for cheatgrass in the grasslands of the Western U.S (Flory, 2010; Knapp, 1998).

- **Ongoing research is exploring the possibility of using prescribed fire to control *Microstegium* invasion.** Prescribed fires will be conducted, and data will be taken on flame heights, fire temperatures, and spread rate. Post-fire surveys will include measures of re-emergence of native herbaceous and sapling communities and Nitrogen cycling. An additional experiment will use altered timing of fire to determine the optimal life history stage of *Microstegium* for control, while exploring the efficacy of using herbicide applications prior to prescribed burns (Flory, 2010).

- **Stage-specific niche requirements may be used as an important management tool.** For example, decreased germination with increased leaf litter represents a limitation of *Microstegium* at the recruitment stage. As stage-specific requirements are identified, these may identify times in the plant's life history when control efforts are most effective (Warren, 2010).

- **Use best management practices; if possible, do not work in or travel through infested areas when plants have set seed or are flowering.** If *Microstegium* patches must be entered while flowering and seeding, complete all work in uninfested areas first, and clean soil and plant material from machinery, boots, and clothing immediately following. If workers must frequently enter *Microstegium* patches, it may be more economical to have designated boots and clothing for infested areas (Evans, 2010a).

- **Land managers should maintain systems for reporting invasive species and establish protocols for *Microstegium* invasion response prior to invasion to maximize EDRR.** All employees and land managers should be able to identify *Microstegium* and other invasive species. Periodically survey the land, especially following disturbance, and indicate any new invasions on a map and flag plants in the field. Immediately implement response protocols when new invasions are found. Additionally, any land users (hikers, hunters, loggers) should be made aware of invasions in the effort to prevent further spread (Evans, 2010a).

- **Land managers should build tenets for prevention and control of spread of invasive species into contracts with outside agencies.** Contracts may include a clean equipment clause; machinery and tools must be clean and void of mud or plant material before arriving for work on managed land. Contracts may require the use of certified weed-free mulch, gravel, or straw, with regulations as part of the Certified Noxious Weed Seed Free Forage and Mulch Program, where standards are set and maintained by the Regional Weed Free Forage Committee of the North American Weed Management Association (NAWMA). Any timber-related activities may benefit from such provisions, including "logging, thinning, prescribed fire, tree planting, road building, trail maintenance, and out-building construction" (Evans, 2010a).

- **The lessons learned from *Microstegium* and the principles of EDRR may be used to combat other invasive species.** Les Mehrhoff told the story of his 2004 visit to Japan, and his first encounter with a new invasive species of concern, wavyleaf basketgrass. Japanese botanist Dr. Takashi Enomoto from the Laboratory of Wild Plant Science at Okayama University, identified wavyleaf basketgrass, *Oplismenus hirtellus* subsp. *undulatifolius* (Ard.) U. Scholz, at Mehrhoff's request and made the statement, "This is weedy; it could be invasive in your country." At that time, neither scientist was aware *O. hirtellus* had already been observed in the US as early as 1996, when it was first collected. It was first reported in 1999 (Peterson *et al.*, 1999), and now there are 7 invasion sites in Maryland, 4 sites in Virginia, and undocumented reports in Pennsylvania. When it was first identified in Maryland at Patapsco Valley State Park, the whole invasion could have been removed in one plastic bag. Today it has spread through the whole forest understory, not unlike a *Microstegium* invasion. However, certain characteristics of *Oplismenus* may make it an even more aggressive invader than *Microstegium*; it is a perennial with sticky fruits. Park service staff have boots and clothing designated for infested areas only, and once it begins to fruit, staff are not allowed in the area. If vigilance and communication had been practiced early, perhaps the invasion could have been prevented. A wavyleaf basketgrass task force was assembled, and met at the National Invasive Species Council offices in Washington, DC on March 31, 2009 (Mehrhoff, 2010).

Challenges and Research Needs

- **Combating *Microstegium* invasion requires education, cooperation, and collaboration.** The needs of the situation are: "identification workshops, informal meetings with towns-people, land managers, administrators, legislators, workshops and conferences". We must "talk to others, develop informational material, get to the popular press", and involve children (Mehrhoff, 2010). Through community networks, detection capabilities may be increased. Increased detection requires increased response capacity. Tenacity and vigilance are prerequisites for invasion response (Ielmini, 2010).

- **Long-range plans must be in place for successful land management.** "Every decision in government is a 30-year decision; think beyond your lifetime in some cases." A long-range plan should account for the future of the climate and the community surrounding the managed land. There should be a clear view of the goals of land management, taking into account future impacts from surrounding un-managed or privately owned parcels of land. "What happens when the board members leave, the money goes up or down, what is the long-term plan?" (Ielmini, 2010).

- **Ecotypic plasticity in populations across a wide geographic range may translate into different ecological effects and management practices for various locations.** Presenters noted a difference in size: 1m tall plants were found in interior forests in Southern Illinois, and tall plants were noted in low light in West Virginia (Evans, 2010b; Huebner, 2010), while plants in New Jersey are about 30 cm tall in dry years, rarely over 40 cm in wetter years (Meiners, 2010). Are these differences a result of climate or unique ecotypes? Is *Microstegium* evolving and adapting to a new range? How do differences impact fire intensity? Do other ecological impacts also vary with associated changes in plasticity?

- **Future research may focus on identifying when and if *Microstegium* produces unique secondary compounds and exploring the relationship between plant chemistry and ecosystem-level effects.** If *Microstegium* does indeed have unique secondary chemistry, under what conditions do plants invest in these metabolically expensive compounds? Could different investment strategies in secondary compounds explain differences observed in denitrification potential in various studies? Studies require an "integrated approach" (top-down and bottom-up) (Wright, 2010).

- **Further investigation into the properties of *Microstegium* secondary chemistry may provide an explanation into the unique tolerances of a C_4 grass which invades low light, mesic environments, when the optimal environments for C_4 grasses are generally high light and more xeric** (Wright, 2010)**.**

- **What ecological interactions occur between *Microstegium* and other invasive species, i.e. *Microstegium* vs. *Alliara petiolata* (garlic mustard)** (Meiners, 2010)?

- **Research has not clearly identified why *Microstegium* is likely to invade high diversity areas.** Environmental factors that facilitate and maintain biological diversity also create good invasion sites for *Microstegium*. What are these factors and how do they influence invasion success? (Meiners, 2010).

- **Studies have documented suspected niche limitations for *Microstegium*; however, a report of failed invasion may hint at possible propagule limitation.** Is there a minimum threshold of available seed required for successful invasion? Data from the Buell-Small Succession Study in the Piedmont Region of New Jersey seemed to indicate some resistance of plots to invasion in the mid-1980's. Plots contained such aggressive invaders as *Rosa multiflora* (multiflora rose), *Lonicera japonica* (Japanese honeysuckle), and other perennials. "Initially few seeds got there and reproduction was unsuccessful, but now there are so many seeds…" Now plots containing these aggressive invaders are being invaded by *Microstegium*. What is the role of propagule limitation in invasion success or failure (Meiners, 2010)?

- **How does herbivory impact *Microstegium* invasions?** Herbivory of *Microstegium* has been documented in the literature; therefore, what is the role of enemy release? Are there reductions in seed production and fitness associated with herbivory of *Microstegium* (Wright, 2010)? Is the forage quality of *Microstegium* tissue equal to native plants for herbivores? Does herbivory of *Microstegium* impact herbivore fitness? Additionally, Bradford *et al.* (2010) raised the question: can *Microstegium* invasion actually increase herbivore numbers in understories of sparse native plants, increasing pressure on native plants and contributing to *Microstegium*'s success?

- **Several factors must be examined in conjunction to determine potential effects on forest regeneration.** Studies indicate that *Microstegium*'s secondary chemistry may inhibit the germination of some tree species. The interaction of allelopathic properties with physical factors, such as thatch production, resource competition, and changes in fire regimes should be incorporated into future studies. Multi-factorial studies are necessary to fully understand impacts on forest regeneration (Wright, 2010).

- **What are the mechanisms behind contrasting effects of *Microstegium* leaf-leachate and invasion on germination rates of different species of trees?** Germination rates of *Liquidambar styraciflua* (sweetgum) seemed to be enhanced by leaf-leachate (Wright, 2010), but in another study conducted in the field, *L. styraciflua* had the lowest germination rate of large and small-seeded species in invaded plots (Flory, 2010). Is the decrease in germination rate a result of an interaction with decreased light availability in invaded conditions? This same Indiana field study showed that larger-seeded trees, oaks and hickories, do not have decreased regeneration in invaded plots, although there was a non-significant trend that warrants further study (Flory, 2010).

- **Experiments must be set up in a way to clearly identify and quantify any negative effects of invasion; experiments such as these may facilitate change in policy and management** (Flory, 2010). Also, currently, there has been no study of the economic impacts of *Microstegium* invasion.

- **Additional work is necessary to test hypotheses concerning *Microstegium*'s effect on the soil microbial community.** Upon decomposition of *Microstegium* litter, there is an increase in the amount of available ammonium and a corresponding increase in the types of microbes which use ammonium. However, reductions in microbial biomass were documented (Fraterrigo, 2010), along with a decrease in carbon pools (Strickland *et al.*, 2009), which suggests possible carbon limitation of the microbial community. Ammonium may be converted to nitrate by autotrophic bacteria, able to fix carbon by using ammonium. These hypotheses would explain how nitrifying bacteria are stimulated to provide greater extractable nitrate in soil from invaded plots (Fraterrigo, 2010). Positive feedbacks between *Microstegium* and the soil community may be a critical factor in invasions with potential implications for management (Lee, 2010).

- **Dynamics for populations at the edge of new invasions may be different than for populations in areas of long-time invasion.** Any differences may have management implications. Existing predictive models for *Microstegium* invasion were developed using dynamics at the edges of new invasions (Shelton, 2010).

- **Do differences in reproductive capacity of edge and interior populations of *Microstegium* indicate true source-sink population dynamics?** Although interior populations produce fewer seeds with less dormancy, they may not be true "sinks". If the "source" or edge population is eradicated, does this lead to a decline in the interior population over several years (Warren, 2010)?

- **Is the fungal pathogen *Bipolaris* sp. a potential control option** (Kleczewski & Flory, 2010)**?**

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