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Integrated Vegetation Management (IVM) for INDOT Roadsides



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16. Abstract

With over 90,000 miles of road in Indiana, it is important that adjoining vegetation be maintained for safety concerns, road structure maintenance and aesthetics. Mowing is currently the main form of vegetation management on INDOT (Indiana Department of Transportation) roadside. Ever-increasing fuel costs and the high labor demand associated with mowing leads to millions of dollars spent on in-house and contract mowing cycles each year. Drastic cost reductions can be achieved by reducing mowing cycles through the incorporation of other management tools including herbicide and native plantings. This study provides data on six herbicide tank mixtures (Milestone/Escort; Milestone/Escort/Plateau; Perspective; Perspective/Plateau; Viewpoint/Streamline; and 2,4-D/Escort/Plateau) and two mowing cycles (one-cycle and two-cycle) at six sites across the state. All herbicide treatments decreased broadleaf cover better than mowing treatments. Herbicide treatments containing Plateau, a plant growth regulator that retards cool-season grass growth, had the shortest grass height. Herbicide mixtures without Plateau were still shorter than mowing plots due to the seedhead suppression qualities found in the selective broadleaf herbicides. A cost savings of over 40% is achieved with one application of herbicide in lieu of one cycle of mowing. Further cost savings can be achieved through the planting of native vegetation, which was the focus of the second portion of this project. Four native seed mixes (western wheat, short grass, tall grass and short grass with forbs) were analyzed for use on right-of-ways. Successful native plantings have reduced maintenance costs for many DOTs across the country by eliminating mowing and herbicide needs. Drought and persistent weeds at study sites resulted in a sparse covering of native species during the year after planting. This is not uncommon for native roadside planting studies since many native grass species require two to three growing seasons to establish.

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EXECUTIVE SUMMARY

INTEGRATED VEGETATION MANAGEMENT (IVM) FOR INDOT ROADSIDES

Introduction

The Indiana Department of Transportation (INDOT) manages right-of-way vegetation on 11,000 miles of roadside. According to INDOT maintenance records, mowing is currently the main form of vegetation management on Indiana roadsides, constituting the third largest time commitment for INDOT employees. While mowing is an important vegetation management tool, it is also expensive, often promotes weeds, and only offers temporary relief from broadleaf weed and grass height concerns. Incorporation of multiple management tools as part of an integrated vegetation management (IVM) program has helped multiple state agencies develop an efficient and effective roadside vegetation program.

The first portion of this study examines the use of herbicide and mowing at six sites throughout the state of Indiana. Two mowing treatments, six herbicide treatments, and an untreated control were compared for their ability to decrease broadleaf species cover and maintain grass height. Mowing treatments included a one-cycle mowing treatment consisting of an early growing season mow (late May to early June 2011) and a two-cycle mowing treatment consisting of both an early (late May to early June 2011) and late growing season mow (August 2011). Herbicide treatments were foliar applied in May 2011 and included tank mixes consisting of aminopyralid (Milestone®), imazapic (Plateau®), 2,4-dichlorophenoxyacetic acid (2,4-D®) metsulfuron methyl (Escort®), and aminocyclopyrachlor (Perspective®, Viewpoint® and Streamline®).

For the second portion of the study, four native seed mixes (western wheatgrass, short grass, tall grass, and short grass with forbs) were evaluated for use as alternatives to traditional non-native roadside vegetation. Determination of successful planting was based on density of planted species one year after planting at six sites throughout the state of Indiana.

Findings

This study evaluated three IVM tools: herbicide, mowing, and native species. Herbicide and mowing were evaluated for management of broadleaf weeds and grass height. Native plantings were evaluated as alternatives to traditional vegetation.

Herbicide Treatments

Broadleaf cover in all six herbicide treatments was reduced rapidly and remained low for 12 months after application. Informal observations also suggest reduced broadleaf presence at 24 months. All herbicide treatments also kept grass under 15 inches for three months after application. All six herbicide treatments regulated grass height equally, therefore we saw no added grass height management benefit in treatments containing imazapic. These results may differ during years with less severe droughts. It was calculated that average herbicide application on INDOT roadsides costs $36/mile and could cover 60 miles/day.

Mowing Treatments

Mowing treatments offered no decrease in broadleaf cover at any point during this study. Grass mowed early in the growing season regrew 7 inches in just two weeks, while grass mowed late in the growing season only regrew 1–3 inches in two weeks. Therefore, waiting until later in the growing season (after all grasses have gone to seed) would result in the longest lasting results for a mowing cycle. One cycle of mowing cost costs $64/mile and can cover 18.5 miles/day, making it a slower and more costly option than any of our herbicide treatments.

Native Plantings

One year after planting, research sites averaged 1.7 native plants per square meter, covering only 6% of the planted area. However, informal visual observations two years after planting suggest that some sites may have become successful. Low cover of native species was likely due to two years of drought. We therefore suggest that native plantings be planned for non-drought years whenever possible, and that further research into planting densities and species selection during drought years be investigated. Weed competition was also a main concern, showing the importance of site preparation prior to planting. Western wheatgrass was the most successful grass species and native forbs were fairly successful at two of the sites.

Implementation

An overall reduction in mowing is essential to reducing vegetation management costs. This can be done by altering current mowing cycles, including herbicide, and planting native species. The results of this study show that a selective broadleaf control herbicide, with the possible addition of growth regulators, offers a longer lasting solution to weed and height control than mowing. A cost savings of over 40% can be achieved with one application of herbicide in lieu of one cycle of mowing. Visual observations showed that one herbicide application reduced broadleaf weed presence not only in the year applied, but also for the two growing seasons that followed. This potential of three years of weed control on INDOT roadsides offers greater cost savings than originally thought. Planting native vegetation offers the potential for even further cost savings by eliminating multiple mowing and herbicide cycles once established.

Research findings were presented at multiple trainings for INDOT, vegetation management organizations, academic programs, and to the public. Many changes to vegetation management on INDOT roadsides have been instituted during the time frame of this project, in part due to the findings presented at these meetings. The timing of the first mowing cycle has been moved to later in the growing season, when grasses will grow less quickly after being cut. Regulations on mowing heights have also been changed in order to prevent killing turf by mowing grass too short. Also, large scale herbicide treatments are being tested, as well as an emphasis on broadleaf control.

Further reduction in mowing cycles may be achieved with native roadside plantings. INDOT has already successfully incorporated native plantings into right-of-ways as part of the Hoosier Roadside Heritage Program. The cost of management in these areas has required drastically less maintenance than the traditional roadside. Although this study resulted in only low cover of native plants the year after planting, visual observations two years after planting show that some sites may indeed be successful. Therefore, further data collection should be conducted to determine success. This study also shows a need for further research into planting during drought years, including planting rates, seed mixes, and management. Lastly, this study shows the importance of site preparation before planting, as well as the large problem that invasive species cause to roadside plantings.

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1. INTRODUCTION

The Indiana Department of Transportation (INDOT) manages right-of-way vegetation on 11,000 miles of roadside. According to INDOT maintenance records, mowing is currently the main form of vegetation management on Indiana roadsides, constituting the third largest time commitment for INDOT employees. This large labor demand results in high maintenance costs. In 2011, INDOT spent over five million dollars on in-house swath and spot mowing; an additional two million was spent on contract mowing. Incorporating other management tools, such as herbicide and native species, may help to reduce vegetation management costs by creating a more stable vegetative community that resists invasion from undesirable plant species.

1.1 Integrated Roadside Vegetation Management

Properly maintained roadside vegetation helps to minimize erosion, improve drainage, support infrastructure, and allow a safe line-of-sight for drivers (*1*). A successful vegetation plan controls weeds, enhances desirable vegetation, is environmentally sound, visually pleasing and cost effective (*2*). Integrated vegetation management (IVM) is a tool for assessing and maintaining desired plant populations by utilizing multiple management tools (*2,3*). IVM is a proactive approach to vegetation management (*4*) that involves an understanding of the biology and ecology of problematic plant species (*5*).

Traditional vegetation management is often highly dependent on mowing as the main or only management tool; however, mowing tends to favor invasive and other weedy species by negatively disturbing vegetation and creating opportunities for weed growth (*6,7*). Incorporating multiple tools as part of an IVM plan (see section 1.3) alters the disturbance regimes in order to give desirable plants a competitive advantage over weeds and invasive plant species (*8*).

1.2 Roadside Weeds

Weed definitions vary, but in general weeds are considered to be any plants that are undesirable, interfere with human activities, or displace desirable plants (*9–11*). On roadsides, this would include plants that cause safety or aesthetic concerns, as well as any noxious weeds that federal and state governments deem a priority to control (*1*). Harsh growing conditions and frequent disturbance from both maintenance and traffic make roadsides an ideal habitat for weeds (*12–14*), which often can tolerate the high-light, poor soil, pollution and disturbance better than traditional turf species (*13*).

Noxious weeds and invasive species are aggressive, adaptable, and hardy, allowing them to out-compete native plant species and other desirable plants for resources (*15*). Roads often act as weed corridors; invasive species spread along these roadside corridors, as well as into adjacent land (*7,16,17*). Invasive plants have the ability to take advantage of fluctuating resources (e.g., increased space and light) released during disturbance (e.g., mowing or tire ruts) and often rebound at a rapid rate, and high density (*18*). These weeds produce large amounts of seed that can remain viable in the soil for years (*19*). Many weed seeds and vegetative parts are carried to roadside habitat by cars and mowing machinery, or come from adjacent land (*7*). In addition, several weedy species have been purposely planted. For example, crown vetch and honeysuckle were introduced to roadsides a few decades ago for their quick growth and erosion control, only to become weedy and invasive (*20*).

1.3 IVM Management Tools

Vegetation management tools can be categorized as mechanical (i.e., mowing, trimming), manual (i.e., chainsaws, string trimmers), chemical (i.e., herbicides), biological (i.e., insect, animals, plant pathogens) or cultural (i.e., native species, treatment timing, fire). A successful IVM plan will utilize several of these tools in order to achieve pre-established vegetation management goals (*2,21,22*). Management plans that utilize only one tool often have limited success, and tend to worsen the weed problem (*21,22*). An understanding of vegetation management tools and the effect they have on the plant community are important to designing an IVM program. This study focused on herbicide (chemical), mowing (mechanical) and the use of native species (cultural) as parts of an IVM program.

1.3.1 Mowing

Mowing is the most common form of vegetation management for transportation agencies across the country (*23*). It is also expensive; with the high cost being attributed to short lasting results, need for multiple treatment cycles, heavy fuel use and large labor demands (*24*). While mowing can control small-scale invasions of certain species, it is highly dependent on the type of roadside vegetation and proper application including timing, frequency and height (*25,26*).

For best weed control, mowing should occur when weeds are beginning to flower but when desirable species are dormant (*26*). Annuals and second-year biennials are most susceptible to mowing during the early stages of flowering (*25–27*). One properly timed mowing may be sufficient to prevent seed set depending on the amount of energy remaining in the plant and the resources available (*25,26,28*).

Frequency of mowing for weed control depends on individual species' responses to being cut. Tolerance of mowing differs by species and depends on growth rate, the number and location of growing points, and the ability to compensate for the temporary loss of energy (food) production that occurs after defoliation (*25,26*). For example, a study of annual sow thistle on rangeland showed control of the weedy species with just one mowing cycle during a drought year. The combination of drought and defoliation was enough to limit recovery of sow thistle after mowing in that year (*28*). Although mowing can have beneficial results on some weeds, others respond to mowing with increased vigor (*25,26*).

Cutting height is another important factor. Cutting too short (i.e., fewer than six inches) can disturb soil, create bare patches and damage desirable grasses (*25*). Grass can, however, be cut short once dormant for the season without harm to the plant (*25,26*). From a weed management perspective it is suggested that weeds are mowed at a height that removes the flower portions of the weed species while leaving the desirable vegetation (e.g., roadside turf grass) intact (*25,26*).

While proper mowing (timing, frequency and height) can be used as a successful tool for weed control, roadside managers must often manage large areas with multiple weed species. Annual species that may be controlled with properly timed mowing are found growing alongside species that respond with vigor when cut, making it difficult to use mowing as a weed management tool on a large scale for swath mowing.

1.3.2 Herbicide

Herbicides kill plants or suppress their growth by disrupting plant growth processes. Non-selective herbicides affect all vegetation because they contain chemicals that affect biological processes found in all plant species. Selective herbicides, on the other hand, target biological processes that only occur in specific plant groups (e.g., broadleaves). Two common types of selective herbicide for roadside use are selective broadleaf control herbicides for broadleaf weed control, and "plant growth regulators" (PGR) for grass height regulation.

Selective broadleaf herbicides target broadleaf weed species. Commercial formulations of these products may contain one or more active ingredients. The chemistry of these active ingredients determines which broadleaf species will be affected (*1*). Residual herbicides can prove useful for many sections of roadside because they remain active in the soil for a specified time period after application, thus preventing seed germination or root growth. It is common practice to "tank mix" (blend) multiple commercial products. While this allows for a large range of target species, it also requires knowledge of the chemicals and their synergistic effects. Although some selective broadleaf herbicides have qualities that also regulate grass growth, others are commonly blended with PGRs. PGRs suppress cool season grass growth for part of the growing season, offering more control over vegetation height (*29–33*).

Herbicide can be an effective, reliable, cost-effective, safe, and easy-to-use vegetation management tool for roadsides. It is especially useful in areas that are hard to reach with mowers, such as guard rail and steep slopes. Several factors should be taken into account when determining which herbicide products to use, including selectivity, residual properties, restrictions of use, mobility in soil, drift potential, environmental safety, ease of use, and cost. Selected herbicides should control the target weed species with minimal off-target issues (*1*).

1.3.3 Native Species

Planting native species on roadsides is one of many forms of cultural vegetation control. Although a complete restoration back to native habitat is neither possible nor desirable for roadside vegetation, native plantings can have many benefits for road managers and the environment (*34*).

The establishment of self-sustaining native vegetation can reduce management costs by limiting the amount of mechanical and chemical controls that need to be used to manage weeds. Stands of diverse native grass and forbs have greater potential to limit invasive species and other weeds through competition (*7,35*) than traditional roadside turfgrass species (*8*). In addition, low-growing native species can meet visibility requirements (*36*). Selection of proper native species therefore could reduce management needs for weed control and height concerns.

Native roadside plantings also have many ecological benefits beyond their potential to limit invasive species. Native plantings can create wildlife habitat (*6,37,38*) and can act as corridors connecting fragmented habitats (*6,39*). This allows plants, insects and wildlife to disperse between areas that would have otherwise been inaccessible. In addition, deep root systems of native prairie plants help prevent erosion (*40,41*), as well as enhance water quality by filtering pollution, reducing runoff and preventing siltation (*40,42,43*).

1.4 Conclusion

Recognizing the value of an IVM approach, INDOT has developed some of the physical and logistical mechanisms needed for implementing an IVM plan. Specifically, the Hoosier Roadside Heritage Program, INDOT's native seed program that provides seed for plantings across the state (*44,45*), has greatly decreased the costs typically associated with native planting programs. In addition, INDOT has developed designs to convert de-icing trucks into herbicide spray trucks during non-winter months. With these programs in place, INDOT was in need of a scientific study that demonstrated the feasibility of IVM practices on a large scale.

This study examines multiple components of an integrated vegetation management plan for INDOT roadsides, including mowing, selective broadleaf control, plant growth regulators and native species plantings. Chapter 2 examines how herbicide and mowing treatments compare in terms of weed control, height reduction, and cost. Chapter 3 examines native seed mixes as an alternative to traditional roadside turf mixes.

2. COMPARISON OF MOWING AND HERBICIDE FOR WEED & HEIGHT CONTROL ON ROADSIDES

2.1 Introduction

With over four million miles of road in the United States (*46*), transportation agencies must manage roadside vegetation to control invasive and weedy species, as well as to maintain a safe vegetation height for the motoring public. To more effectively maintain roadside, managers are progressing toward integrated vegetation management (IVM) (*2*). An understanding of vegetation management tools and their effect on the plant community is important to designing a successful IVM program. Mowing and herbicide application are two common practices in IVM. The success (or lack of success) of both of these tools in managing vegetation is dependent on how they impact the growth of current vegetation. This impact can come in the form of plant death, defoliation, or stunted growth. The frequency (e.g., number of annual mowing cycles or herbicide applications), timing (e.g., which season or during what plant growth stage), and intensity (e.g., mowing height or herbicide efficacy) of vegetation management play an important role in determining how the vegetation is impacted (*25,26*). Changes to current management practices may allow transportation agencies to control weedy species and vegetation height more effectively and efficiently.

2.1.1 Broadleaf Weeds

Herbaceous broadleaves can cause line-of-sight obstructions and are often weedy or invasive species. Although not all broadleaves are a concern, roadside vegetation management often aims to reduce the total presence of broadleaf species on roadside in order to minimize risks and maintain vegetation heights at approximately 8 to 12 inches (20 to 30 cm). If used properly, mowing or herbicide can shift the roadside plant community toward a grass-dominant right-of-way (*47*). This shift is attributable to differences in the growing characteristics of different plant species including how fast it grows, growth stage (e.g., seedling, rosette, flowering), number/location of growing points (area of the plant were cells multiply and vegetative growth occurs), and life cycle (e.g., annual, biennial, perennial) (*25,26*).

Mowing to control broadleaves is most effective during the flowering stage, when energy (food) storage is highest in above ground tissue (*47*). Mowing at this time reduces seed output and can limit regrowth because most of the plant's energy has already been consumed (*25–27,47*). For annuals and second year biennials, one properly timed mow may be enough to prevent seed dispersal for that year (*25,26,28*). However, many roadside species show little control from mowing or respond with increased vegetative growth when cut (*25,26*). First year biennials, herbaceous simple perennials, and creeping perennials have growing points and energy storage either at or below the soil surface. In many cases, mowing does not harm these growing points or meaningfully decrease stored energy (*11*), thus allowing for consistent regrowth (*47–50*).

The diversity of roadside weeds and the scale at which transportation agencies must manage vegetation make it difficult to utilize mowing as the sole maintenance tool (*26*). For this reason, IVM programs often utilize selective broadleaf control herbicides to manage broadleaves and other vegetation (*2*). The impacts of herbicide use are highly dependent on plant characteristics (e.g., growth stage, leaf shape, cuticle, and height), herbicide characteristics (e.g., mode-of-action, rates) and their interactions (e.g., selectivity, penetration, translocation, and metabolism). Selectivity in herbicide can allow for the removal of target weed species without unnecessary harm to desirable species. The ability to remove specific weedy plants allows for desired turf species to utilize the light, space, water and nutrients that may have otherwise been consumed by the weeds. When large weed infestations are removed, it is important to limit the amount of weed reemergence in order to allow time for desirable species to fill in the area. For this reason, herbicide mixes utilized on roadsides often contain "residual" properties, meaning they remain active in the soil to prevent reemergence of the plant by killing or injuring germinating weed seedlings (*11*).

2.1.2 Grass Height

Once the shift to a grass-dominated roadside has occurred, management can focus attention on maintaining grass at a safe height. The criterion for safe vegetation height varies among transportation agencies in the U.S., with desired height maximums ranging from 30cm (12 in) to 56 cm (22 in) (*51*). Unlike broadleaf management, the goal for managing grass height is to minimize regrowth without permanent harm to the plant.

Successful grass height control is dependent on the frequency, timing, and cutting height of mowing cycles (*51*). Many states recommend a 15 cm (6 in) mowing height (*51*). Because grasses have growing points at the soil surface (*52*), mowing does not halt growth and the plant will continue to grow until seed formation, inadequate weather, or resource (water/nutrient) depletion. This capability of grasses leads many managers to arrange for intensive mowing (e.g., multiple annual cycles and short cutting heights) of roadsides to keep grass at desired heights. However, mowing every month or even every two months (*53*), or mowing fewer than 5.1 cm (2 in) (*54*), has been shown to reduce energy storage, eventually harming grasses. Studies suggest that mowing once a year, either at the beginning or end of the growing season, or every three months allows grass to store the most energy in stem bases and basal crowns (*53*). This allows grass adequate time to replenish energy stores between mowing cycles, thus resulting in less killing of turf.

The application of growth regulation herbicides can help limit grass growth between mowing cycles. While the desired result of broadleaf herbicides is to kill the plant, plant growth regulators (PGR) are applied to alter plant growth without killing the plant (*55*). Imazapic, a common growth regulator used on roadside turf, is in the amino acid inhibitor herbicide class and works by interrupting plant cell growth (*11*). In addition to imazapic, many herbicide chemistries utilized for broadleaf control also slow grass growth without killing the grass.

2.1.3 Objectives

The main objective of this study was to compare two mowing and six herbicide treatments for control of broadleaf species prevalence and grass height growth. This study set out to mimic the herbicide and mowing procedures of the Indiana Department of Transportation (INDOT) and included large-scale test plots that focused on real-world application. Study sites were located on roadside and represented a comprehensive range of roadside conditions.

Success of broadleaf control was evaluated based on the comparison of visual percent cover estimates taken prior to the beginning of the study (Month 0) and the percent cover at five inventory times thereafter (Months 1, 2, 3, 4, and 12). Treatments with the highest reduction of broadleaf cover were considered most successful. Vegetation height measurements were taken at the same time as percent cover data. Grass height regulation was evaluated based on two factors: if grass was kept below the maximum height for safety, and how long the reduced height lasted after mowing or herbicide application.

It was predicted that herbicide would provide better broadleaf management and grass height regulation than either mowing cycle treatment. In particular, it was predicted that treatments containing the new herbicide aminocyclopyrachlor would provide more broadleaf control than other established herbicide chemistries such as 2,4-D, to which some plant species are developing a resistance (*56–58*). Lastly, it was predicted that grass would remain shorter in treatments containing the PGR imazapic in addition to selective broadleaf chemistries.

2.2 Methods

2.2.1 Installation

Six sites were located throughout the state of Indiana; one in each of INDOT's management districts (Figure 2.1). Sites were evenly distributed between Indiana's southern, central, and northern regions in order to compare regional differences among treatments. Sites were located on state roads (La Porte, Crawfordsville, and Seymour Districts), medians (Fort Wayne and Greenfield Districts) and interstate (Vincennes District). Each site consisted of approximately 24.1 km (15 mi) of roadside with at least 5.5 m (18 ft) of vegetation between the road and adjoining property. Selected sites were relatively free of lawns, bypasses, bodies of water, or other areas where herbicide application was not feasible.

Each site contained three plots of each treatment. Plots were 0.8 km (0.5 mile) long by 5.5 m (18 ft). This large plot size was chosen in order to accommodate the full herbicide spray width and allow INDOT managers to compare treatments. Permanent sampling points were established within plots in order to identify changes in species composition over time. Each plot had five sampling points, spaced 100.6 m (330 ft) apart and 2.7 m (9 ft) from the shoulder.

2.2.2 Treatments

Treatment selection was based on current INDOT management practices and designed to simulate real-world vegetation management. Mowing is the most common form of roadside vegetation management for INDOT, as well as transportation agencies across the country (*23*). At the time of this study, standard INDOT mowing practices involved one to three annual mowing cycles beginning in late May or early June. Herbicide practices varied greatly between INDOT districts and subdistricts in terms of product preferences and frequency of use. For this study, two mowing treatments, six herbicide treatments, and an untreated control were compared for their effectiveness in reducing broadleaf species cover and grass height. The untreated control received no herbicide or mowing, with the exception of a few spot treatments of the invasive species Johnsongrass at the southern sites, for legal and safety purposes.

Mowing treatments included a one-cycle mowing treatment (consisting of an early growing season mow) and a two-cycle mowing treatment (consisting of both an early and late growing season mow). The early season mowing occurred in late May in the southern portion of the state and early June in the northern

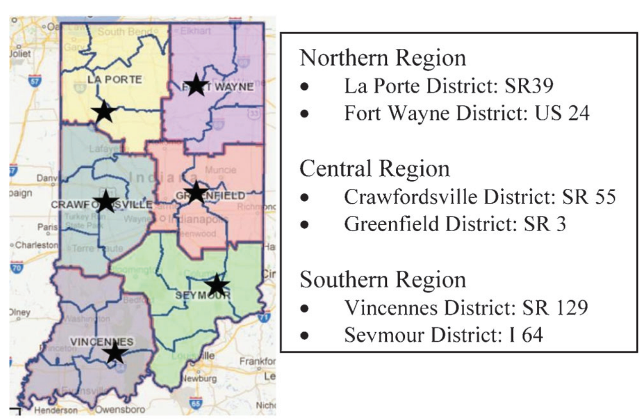


Figure 2.1 Map of the six treatment sites (black stars) and the corresponding Indiana Department of Transportation Districts (colored areas).

regions; approximately two weeks after herbicide application in the herbicide treatments at all sites. The late season mowing occurred in August, approximately three months after the first mowing cycle. Exact heights were not recorded directly after mowing, but mowing height was set to approximately 20 cm (8 in), which falls within the mowing height range suggested by INDOT. Mowing was performed by INDOT using standard commercial mowing equipment.

Herbicide treatments included selective broadleaf control and grass growth regulation mixes. Because vegetation control depends on the herbicide's mode-of-action, it is common practice to mix herbicides to achieve control over a wider range of target species. This is of particular importance because a wide range of weeds can be found along stretches of roadside. For this study, seven products were mixed in various combinations to create the six treatment mixes (Table 2.1). Herbicide treatments T1–T3 were tank mixes currently in use on INDOT roadside vegetation and included combinations of the selective broadleaf chemistries 2,4-dichlorophenoxyacetic acid (2,4-D®), aminopyralid (Milestone®), and metsulfuron methyl (Escort®), as well as the grass growth regulator imazapic (Plateau®). Treatments T4-T6 contained products that were new on the market including Perspective®, Viewpoint® and Streamline®. These latter three treatments all included the newer chemistry aminocyclopyrachlor, which comes pre-mixed with other chemistries meant to offer both broadleaf and grass regulation. Imazapic was added to one of the Perspective® treatments to evaluate any synergistic grass regulation responses from mixing these chemistries. A non-ionic surfactant, Invade 90, made up 0.25% by volume of all tank mixes.

Herbicide treatments were applied with a research sprayer designed to accurately simulate the equipment, technology, and process used by managers when treating roadsides (Figure 2.2). Tank mixes were applied using six 378.5 L (100 G) tanks on a skid sprayer pulled at 12 mph. A Raven Flow Meter® was used to regulate an approximate pressure of 175 kPa (25 lbs/in^2). A XP BoomJetTM® nozzle was utilized and produced a spray pattern 5.5 m (18 ft) wide at a rate of 230 L/ha (25 gal/ac). Application began at the southern sites in early May 2011, moving northward over a period of three weeks.

In addition, three of the six herbicide treatments received an initial-cut (i.e., an early season mowing that occurred during the same time mowing treatments received their early growing season mow). One site from each region was selected for this initial cut in herbicide plots: La Porte (northern region), Greenfield (central region), and Vincennes (southern region) District sites. These treatments were also mowed at a height of 20 cm (eight inches). This decision was made in response to the delay in herbicide application due to weather conditions.

TABLE 2.1
Management components of herbicide and mowing treatments.*

Treatment/Products		Rate	Ingredients	Treatment Description
T1	2-4D® Dow Escort® DuPont Plateau® BASF	1 qt/a 0.5 oz/a 3 oz/a	2,4-dichlorophynoxyacetic acid metsulfuron methyl imazapic	Broadcast foliar herbicide (broadleaf control & grass growth regulation)
T2	Milestone® Dow Escort® DuPont	7 oz/a 0.5 oz/a	aminopyralid metsulfuron methyl	Broadcast foliar herbicide (broadleaf control & grass growth regulation)
T3	Milestone® Dow Escort® DuPont Plateau® BASF	7 oz/a 0.5 oz/a 3 oz/a	aminopyralid metsulfuron methyl imazapic	Broadcast foliar herbicide (broadleaf control & grass growth regulation)
T4	Perspective® DuPont	3.5 oz/a	aminocyclopyrachlor chlorsulfuron	Broadcast foliar herbicide (broadleaf control & grass growth regulation)
T5	Perspective® DuPont Plateau® DuPont	3.5 oz/a 3 oz/a	aminocyclopyrachlor chlorsulfuron imazapic	Broadcast foliar herbicide (broadleaf control & grass growth regulation)
T6	Viewpoint® DuPont Streamline® DuPont	1.58 oz/a 1.46 oz/a	aminocyclopyrachlor metsulfuron methyl imazapyr aminocyclopyrachlor metsufluron methyl	Broadcast foliar herbicide (broadleaf control & grass growth regulation)
T7	1 Mowing Cycle	NA	NA	Early season mow
T8	2 Mowing Cycle	NA	NA	Early & late season mow
T9	Control	NA	NA	NA

*At Fort Wayne, Greenfield, and Vincennes District sites herbicide treatments received an initial mowing at the same time as the mowing treatments. Herbicide treatments received an initial mowing at the same time as the mowing treatments.

Figure 2.2 Photograph of research skid sprayer holding six 100-gallon herbicide tanks.

Daily precipitation made it difficult to plan application times when herbicide would have at least two hours to become rainfast. Flooding also blocked roads and required the majority of INDOT resources. By the time flooding subsided, much of the vegetation was already taller than desired with some species already having gone to seed. Mowing addressed any safety and aesthetic concerns while at the same time allowing more data on plant growth regulation and seedhead suppression. This was also standard operating procedure for INDOT and ensured the research was conducted under real world policies. While this did affect grass height data, no differences were seen in broadleaf cover between sites with and without this initial-cut.

2.2.3 Vegetation Inventories

Preliminary vegetation inventories (Month 0) for all treatments were taken at the time of herbicide application in May 2011. Subsequent inventories were taken at one, two, three and four months after application, as well as a final inventory one year (Month 12) after application. The final inventory occurred in May 2012 prior to the first mowing cycle of the season. Maximum height and percent cover were recorded for each species rooted within a 1-m^2 hoop placed at each sampling point. Pictures were taken at the same location at each inventory time in order to compare changes in vegetation. Each black or white block on the right of the photoboard (as seen in photographs at end of this chapter) is 2 inches while each center block is 1 foot).

2.3 Results

All herbicide treatments reduced broadleaf weeds for over a year and regulated grass growth for multiple months. Mowing treatments showed no broadleaf reduction, and grass cut during the early mowing cycle grew back rapidly. Pictures of treatments can be seen in the conclusions (section 2.5).

2.3.1 Broadleaf Control

Prior to the start of the project, the Vincennes site had two to four times more broadleaf cover of any other site, with 27% broadleaf cover compared to the 6–12% broadleaf cover at the other five sites (Figure 2.3). Despite these initial differences, similar trends in the percent cover of broadleaves (Figure 2.4 and Figure 2.5), grass (Figure 2.5) and bare ground (Figure 2.5) were seen at all sites. These trends included:

- *Control Plots:* Broadleaf cover increased slightly, from 11% to 14% throughout the study. Bare ground decreased as vegetation (both grass and broadleaf weeds) filled in the bare areas throughout the growing season.
- *Herbicide Plots:* Herbicide offered the best broadleaf weed management, with broadleaf cover decreasing rapidly (from an initial 13%, to 2% within the first month) and remaining low (<2%) throughout the entire growing season and even into the following growing season. The initial decrease in broadleaf weed cover led to a temporary increase in bare ground; however, this bare ground began filling in with grass by the second month. All six herbicide treatments showed similar results in overall broadleaf control. Visual inspection of

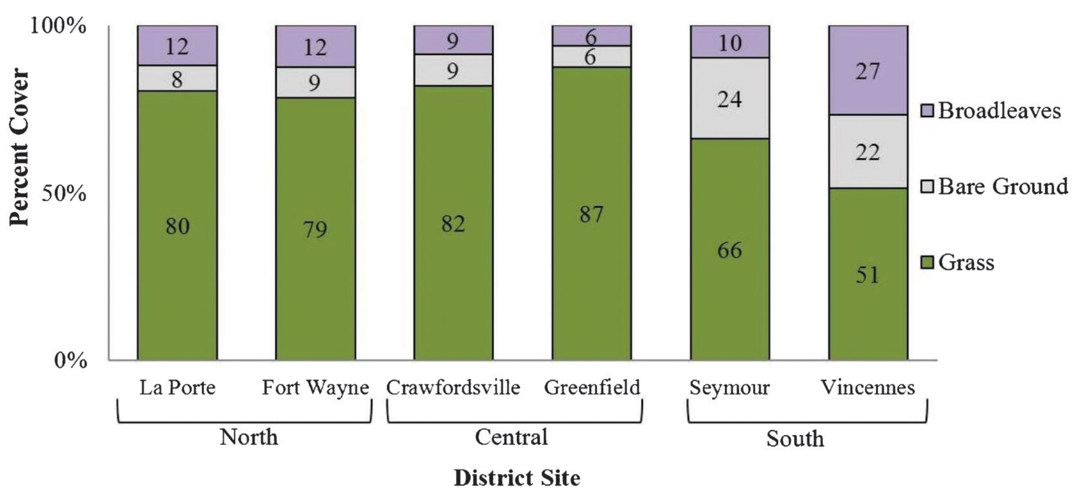
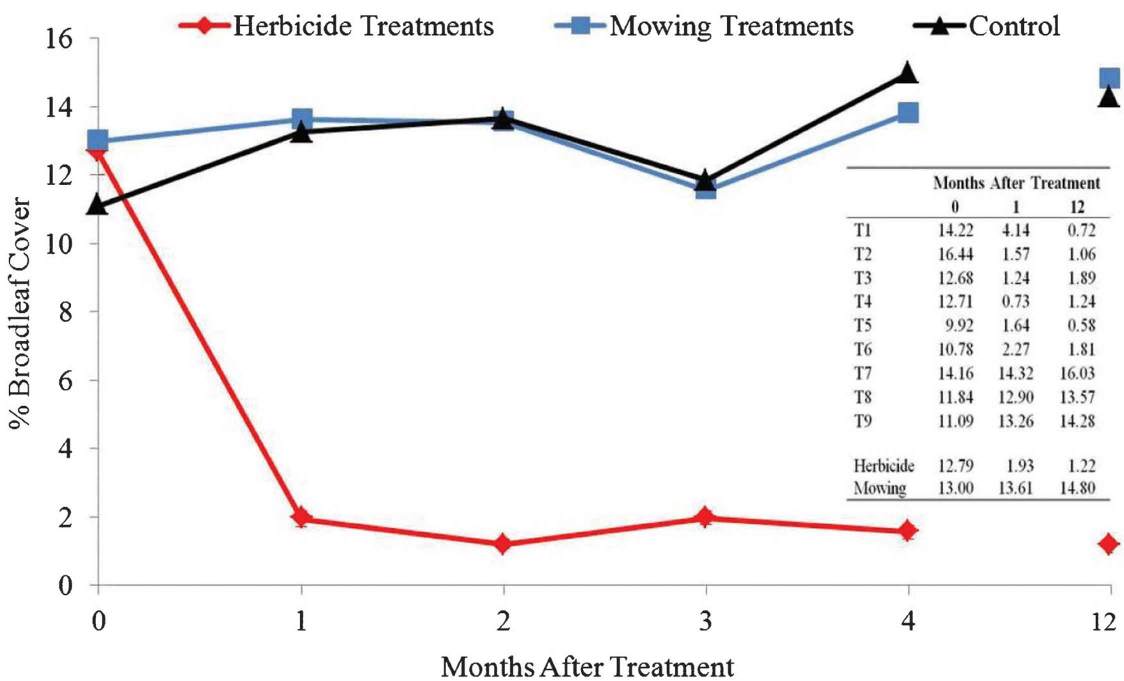


Figure 2.3 Percent cover of broadleaves, grass, and bare ground for each site at the start of the experiment (Month 0).



	Months After Treatment		
	0	1	12
T1	14.22	4.14	0.72
T2	16.44	1.57	1.06
T3	12.68	1.24	1.89
T4	12.71	0.73	1.24
T5	9.92	1.64	0.58
T6	10.78	2.27	1.81
T7	14.16	14.32	16.03
T8	11.84	12.90	13.57
T9	11.09	13.26	14.28
Herbicide	12.79	1.93	1.22
Mowing	13.00	13.61	14.80

Figure 2.4 Percent broadleaf cover over time for herbicide treatments (T1–T6 average), mowing treatments (T7–T8 average) and the control (T9). Inset: box shows the average percent broadleaf cover for each treatment at Month 0, Month 1, and Month 12. (see Table 2.1 for treatment descriptions).

sites two years after application shows that herbicide treatments still had reduced broadleaf cover.

- *Mowing Plots:* Neither mowing treatment decreased the presence of broadleaf weeds. Although mowing removed the upper portion of the broadleaf weeds, thereby making them less visible for a short period of time, the amount of broadleaf cover present in these plots did not decrease. The amount of bare ground in mowing treatments continually decreased over time, as plants (both grass and broadleaf weeds) grew throughout the growing season. Overall, mowing treatments showed no control over broadleaf weed.

A total of 37 different species were recorded at the study sites prior to any research management practices. Greenfield had the fewest broadleaf species (14 species), while Vincennes had the most (24 species). Only nine species (*Lotus corniculatus, Conyza canadensis, Plantago lanceolata, Trifolium repens, Melitotus sp, Trifolium pretense, Daucus carota, Cichorium intybus*, and *Taraxacum officinale*) averaged over 0.5% cover across all sites and none were above 2% cover. The number of broadleaf species increased in the one-cycle mowing treatment (34 species), two-cycle mowing treatment (32 species) and control (30 species) within the year. The number of broadleaf species in herbicide treatments decreased (average of 9 species) after a year, with individual treatments ranging from five species in T5 to 12 species in T6. The species found within herbicide

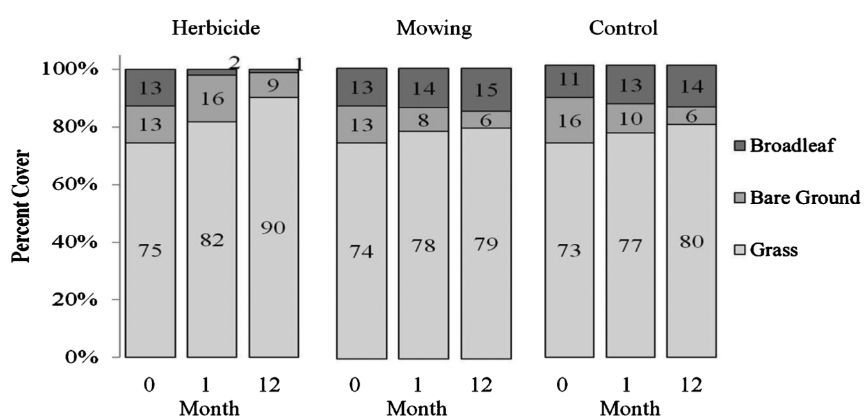


Figure 2.5 Average cover of broadleaves, grass, and bare ground in herbicide treatments, mowing treatments, and control plots at Month 0, Month 1, and Month 12.

treatments one year after application included *Lotus corniculatus, Conyza canadensis, Plantago lanceolata, Trifolium repens, Melitotus spp., Trifolium pratense, Daucus carota, Cichorium intybus, Taraxacum officinale, Solidago spp., Plantago major, Asclepias verticillata, Ambrosia artemisiifolia, Cirsium arvense, Convolvulus arvensis, Xanthium sp., Euphorbia esula, Portulaca sp.*, and *Leucanthemum vulgare*. None of these species averaged above 0.2% cover and no differences were seen among treatments.

2.3.2 Grass Growth Regulation

Sites were divided into two groups for height analysis: initial-cut (Fort Wayne, Greenfield and Vincennes Districts) and no-initial-cut (La Porte, Crawfordsville, and Seymour). Initial-cut sites were those in which herbicide treatments received an early season mowing cycle. Although the graphs are displayed separately (Figure 2.6), similar trends were seen in both of these groups. These trends are as follows:

- *Control:* As would be expected, grass in control plots was taller than grass in all other treatments. This was true throughout the four months of height data analyzed, although some treatments reached heights close to those in the control by Month 4. Despite not being managed, grass height remained below an average of 76 cm (30 in), which may be an acceptable height in many locations. Rapid growth occurred between Months 0 and 1 of this study (May into June) when height nearly doubled, growth then slowed or height decreased during the summer heat.
- *1st Mowing Cycle:* The first mowing cycle decreased grass height from an average of 38 cm (15 in) at the start of this project in May (i.e., at Month 0) down to 20 cm (8 in). In only two weeks (i.e., at Month 1), grass had regrown to heights of 38 cm (15 in) or above—an increase of 18+ cm (7+ in).
- *2nd Mowing Cycle:* The second mowing cycle, occurring in August (i.e., 2.5 months after the project start), decreased grass height back to 20 cm (8 in) in two-cycle mowing treatments. Grass regrew only one to three inches in the two weeks after the mow (Month 3).
- *Herbicide:* At the sites with no initial-cut, the initial grass height measurement was 38 cm (15 in) inches and grass remained at 38 cm (15 in) for 3 months. At sites with the initial-cut, initial grass height was 40 cm (16 in) before being cut to a height of approximately 20 cm (8 in). Although grass height did increase after this cut, it remained at 25 cm (10 in) during Months 1 and 2, and was still under 38 cm (15 in) at Month 3.

2.4 Discussion

This study evaluated the use of herbicide and mowing as IVM tools to control broadleaf weeds and grass height on Indiana roadsides. All herbicide treatments contained chemicals designed to both control broadleaves and regulate grass growth. As predicted, herbicide treatments controlled broadleaves and suppressed grass growth better than mowing treatments. All six herbicide treatments had similar results in regards to both grass and broadleaf management.

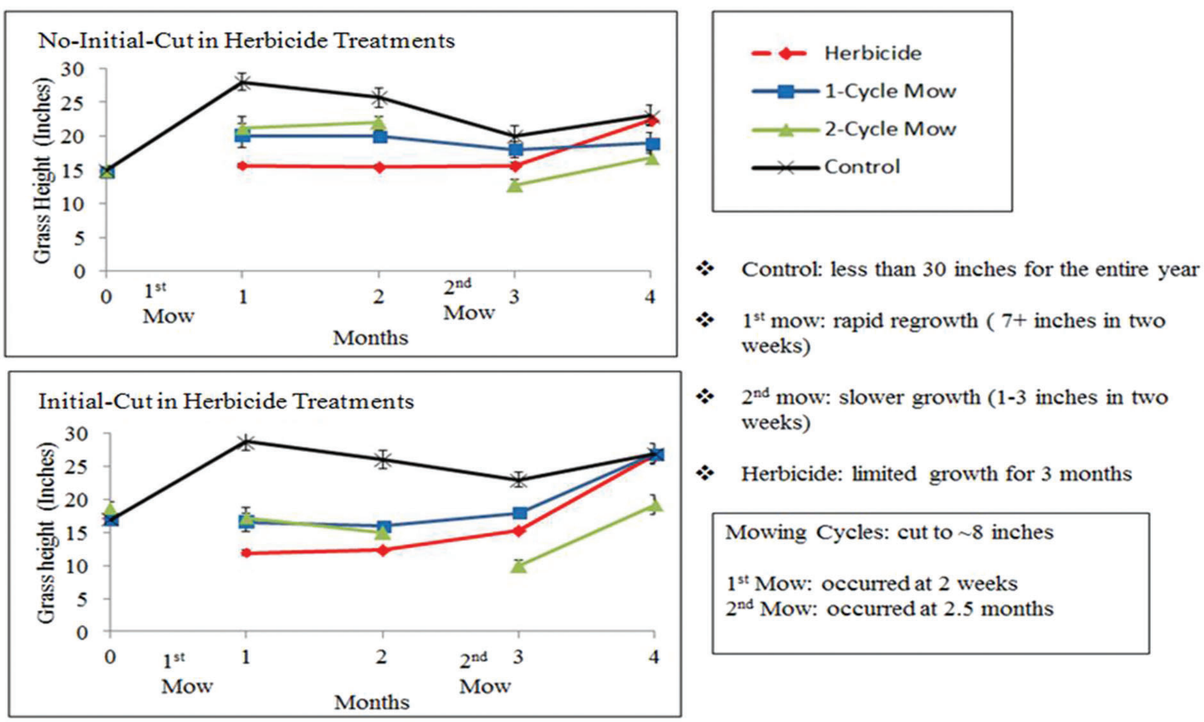


Figure 2.6 Changes in grass height over time. Sites are grouped into those that received no-initial-cut (top) and those that did receive an initial-cut (bottom); see end of section 2.2.1 for description of these groups.

Broadleaf Control. Determination of broadleaf control was based on how well treatments minimized broadleaf cover. As expected, herbicide treatments provided the greatest control over broadleaf weeds; providing rapid decreases (from 13% to 2% within one month after application), and control throughout the study period (1% one year after application). Although there were differences in the effect of herbicide treatments at Month 1, all herbicide treatments reduced broadleaf cover relative to mowing. At Month 2 and thereafter, all herbicides performed equally in broadleaf reduction, and there were also no differences in control of any individual broadleaf species. The prediction that newer herbicide chemistries would provide more broadleaf control than 2,4-D was therefore not supported; however, weed species with reported resistance to 2,4-D, such as *Amaranthus palmeri*, were not common within our study sites. Consequently, we cannot suggest one herbicide treatment over another based on broadleaf weed control alone.

In contrast, mowing treatments showed no decrease in broadleaf cover over time and had levels equivalent with those found in control plots, which received no management. Although mowing treatments did not affect broadleaf cover in this study, the disturbance from mowing has been associated with increases in broadleaf weed cover in other studies. Canada thistle, a problematic species for roadside managers, has been found to respond to mowing with increased stem counts (*59*) and growth of new plants (*60*). The same is true for many other biennial and perennial species that continue to grow after being mowed (*11,47–50*); some with increased vigor in response to the disturbance (*25,26*). Further spread of weeds can come from the transport of broken root segments, stolons, and rhizomes (*27*) or introduction of seeds (*61*) by mowing equipment. This introduction of weedy plants, coupled with shifts in dominant species due to defoliation from mowing (*22,25,26*), changes in light intensity (*62*) and the creation of bare ground (*25*), can allow for the spread of weeds along road corridors.

Grass Height. Success of grass height regulation was evaluated based on the length of time that grass remained under the maximum height required for safety. Grass was shortest in herbicide treatments during Month 1 and Month 2, and in T8 during Month 3 and Month 4. T8 was the only treatment to receive the end of year mowing cycle. It therefore had the shortest grass at the end of the growing season even though the herbicide treatments provided the longest lasting grass height regulation.

No differences were seen among herbicide treatments; therefore, the prediction that treatments containing imazapic would provide added height regulation was not supported. Herbicide treatments kept grass height at or below 38 cm (15 in) for three months. While this was above the 30 cm (12 in) recommendation by agencies such as the Missouri DOT and Nebraska Department of Roads, it was still below other recommendations of 45 or 56 cm (18 or 22 in) (*51*). In contrast, the early season mowing cycle (in T7 and T8) saw grass height increase from the 20 cm (8 in) cutting height to 43 cm (17 in) in just two weeks. The late season mowing cycle (in T8), however, increased only 8 cm (3 in) in two weeks and only 25 cm (10 in) in the six weeks after mowing. Therefore, herbicide provided the overall best regulation over grass height.

Because the results of the early season mow were short-lived, multiple mowing cycles would be necessary to provide the same height control that just one application of herbicide provided. Inclusion of herbicide in an IVM program for grass height could therefore increase the length of time between mowing cycles. While grass height may be a management concern in certain areas, the need for grass height regulation through either mowing or herbicide is dependent on the species present (*54*) and precipitation (*51*).

2.4.1 Management Implications

2.4.1.1 Cost. Short-lasting results, need for multiple treatment cycles, heavy fuel use, and large labor demands make mowing an expensive management tool (*24*). In addition, management plans that utilize only one tool often have limited success, worsening the weed problem and requiring additional management (*21,22*). Incorporation of multiple management tools as part of an IVM program has helped state agencies reduce roadside vegetation costs (*63,64*).

Based on INDOT management records in 2010, a single cycle of in-house mowing cost $64.32 per mi. ($39.77/km) for a 10 foot (3 m) swath. This included all costs (i.e., vehicles, gas, maintenance, labor, and time off) and is based on the average district utilizing four workers, one truck, and three mowers. In comparison, herbicide application costs $36.67 per mi. ($22.79/km) for a 10 foot (3 m) swath based on the use of three people, one herbicide sprayer vehicle, and one truck with an arrow board to provide traffic control. The main cost savings come from the reduction in time associated with herbicide application compared to mowing. Sixty miles of roadside can be managed per day with herbicide, compared to 18.5 miles with mowing with current INDOT equipment. However, weather conditions such as wind, humidity, precipitation and temperature limit the timing of herbicide more than mowing.

2.4.1.2 Safety. Safety considerations for employees, the public and the environment are important when selecting the proper IVM tool. Mowing has been described as the most hazardous form of vegetation management because the slow speed and frequency of mowing puts maintenance crews near traffic for extended periods of time (*23*). Broadcast herbicide, on the other hand, can be applied to areas faster than with mowing and needs fewer annual cycles, thereby limiting the amount of time management crews and motoring public come in contract. Maintenance crews also remain in vehicles during application and can reach places that would be difficult with a mower such as slopes, guard rails, and cable rail (*65*). From an environmental perspective, heavy consumption of fossil fuel along with high levels of pollutants in mower exhaust make mowing a less appealing option than some other management tools.

Herbicides introduce chemicals into the environment that can cause undesired off-target effects. When registering a pesticide, the EPA considers data on how the chemical affects wildlife and aquatic organisms, non-target insects, plants, the environmental fate of the chemical, the residual chemistry, and spray drift potential (*66*). Spray drift and water contamination are the two main off-site concerns. Selection of proper spray nozzles, addition of drift control additives, and application during favorable weather conditions will help roadside managers control drift. Knowledge of the herbicides' interaction within the environment will also help limit soil and water contamination (*67*).

The newer chemistries in this study (metsulfuron methyl, aminopyralid, and aminocyclopyrachlor) have all been recommended as having low dose rates, low toxicity to mammals, and a favorable environmental profile (*68–72*). However, all have potential for drift and for groundwater contamination, especially in areas with highly permeable soils or where the water table is shallow. 2, 4-D has been used in the United States since the 1940's and it has been reported that some weed species have developed a resistance (*56–58*).

2.4.1.3 Weather. Weather conditions such as temperature and precipitation can alter management needs and the effectiveness of management tools. In April and May 2011, heavy rains and flooding delayed herbicide application. High temperatures and a summer long drought began in June 2011. While these extremes were unfortunate from a research standpoint, they also represent a challenge for real world application. Certain herbicides require precipitation in order to percolate into the soil where they can be taken up by roots; heavy rain may cause others to leach through the soil or wash off of plants before they can become effective. Utilizing herbicide as a management tool may require prioritizing herbicide application so that it can be applied during the proper weather conditions. In addition, mowing during a drought, or when soil and plants are wet can also damage vegetation.

In general, vegetation grows more slowly and there are fewer and less vigorous weeds when soil moisture is limited during drought conditions. In many instances, mowing cycles can often be reduced or eliminated during these times (*51*). This not only reduces management cost, but also does less damage to desirable turf. Application of herbicides during droughts is also unlikely to be beneficial. The herbicides used in this study were all systemic, meaning they had to be translocated from the point of contact to the target areas within the plant in order to have an effect. However, during times of water-stress, movement of water and sugar, and therefore herbicide, is limited. Evidence of reduced herbicide efficacy under dry conditions is well documented (*73–75*).

The drought of 2011 began approximately a month after herbicide application, allowing herbicides to affect plants prior to water-stress conditions. However, drought likely reduced reemergence of weeds and limited grass growth. Therefore, our observations of broadleaf efficacy and grass growth regulation of all treatments might have been different if plants had not been water-stressed.

2.4.1.4 Herbicide Selection. All six herbicide treatments in this study showed a similar ability to reduce broadleaf weeds and regulate grass growth, and therefore could be recommended for roadside vegetation management. Still, recommendations can be made in herbicide selection based on this study. Since all herbicide treatments had similar trends in grass height over time, the addition of imazapic (a PGR added for increased grass growth regulation in T1, T3 and T5) may not be necessary. T2 (Milestone/Escort) and T4 (Perspective) showed the same amount of growth regulation as treatments T3 (Milestone/Escort/Plateau) and T5 (Perspective/Plateau). In treatments without imazapic, the broadleaf control herbicides provided adequate grass height regulation for the 2011 growing conditions. Omitting the additional PGR may reduce some cost and also reduce risk of misapplication. However, in areas where broadleaf weeds have been managed and are minimal, application of an herbicide mainly designed for grass growth regulation can help limit mowing cycles and could therefore help reduce vegetation management costs.

It was also noted that T6 (Viewpoint/Streamline) showed more turf discoloration than the other treatments. This discoloration was temporary and mostly apparent in the southern sites. Most vegetation managers that witnessed this effect believed that the discoloration was still acceptable. Perspective (T4 and T5), which contains the same active ingredient (aminocyclopyrachlor) as Viewpoint and Streamline, did not have the same discoloration issues. We therefore suggest using Perspective over our treatment of Viewpoint and Streamline.

2.5 Conclusion

While mowing is currently the dominant form of roadside vegetation management, this study shows that mowing does not provide the desired control over grass and broadleaf species and is more expensive than an IVM approach (Table 2.2). Differences in treatments can be seen in the photographs taken throughout the study (Figure 2.7, Figure 2.8, Figure 2.9, Figure 2.10, and Figure 2.11).

All herbicide treatments decreased the prevalence of broadleaf weeds and provided grass growth regulation, thereby eliminating many of the aesthetic and height issues associated with broadleaf weeds. This reduction in broadleaves can help eliminate or reduce costly and

TABLE 2.2
Comparison of mowing and herbicide for broadleaf control, grass height regulation and cost.

	Broadleaf	Grass	Cost
Mowing	No decrease in broadleaf cover (remained ~14%)	Rapid regrowth after early season mow (7 inches in 2 weeks), slower regrowth after late season mow (1–3 inches in 2 weeks)	1 mowing cycle costs $64/mile and can cover 18.5 miles/day
Herbicide	85% decrease in broadleaf cover (remained <2% cover)	No growth for 3 months at no-initial-mow sites	1 herbicide application costs $36/mile and can cover 60 miles/day

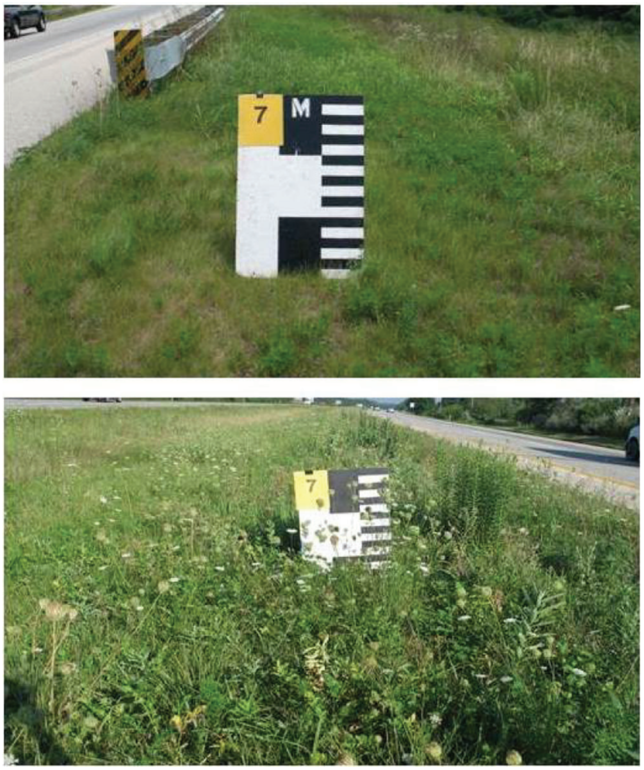


Figure 2.7 Photographs of broadleaf weeds in a T7 (one-cycle mowing) treatment. At Month 1 (top), broadleaves are short due to mowing, but still present. At Month 3 (bottom), broadleaves have increased in height and become the main aesthetic and height safety concern.

ineffective mowing cycles by creating roadside that is predominantly grass. Broadleaf cover in herbicide treatments was reduced rapidly and remained low for 12 months, with visible results still seen after 24 months. Therefore, herbicide offered weed control not only in the year applied, but also for the two following growing seasons Although no numerical data was collected at Month 24, pictures show the reduced broadleaf presence in herbicide treatments compared to mowing treatments (Figure 2.10).

Furthermore, this study shows that early season mowing yields short lived results for height regulation. Grass only took two weeks to return to the height prior to the mow; an increase of over 7 inches in two weeks. In comparison, grass only grew one to three inches in two weeks when cut later in August after most grasses have gone to seed. This suggests that INDOT, and other agencies managing vegetation, would see cost benefits from delaying the first mowing cycles until later in the growing season. While there are certain areas that may not be able to forgo mowing until later in the season, height would likely not be an issue along many stretches of roadside.

Grass heights in areas receiving no management (i.e., controls) reached a maximum height of 30 inches in Month 2 and then decreased in height as the plants became dormant during the heat of the summer. Although 30 inches is above the recommended safety height for many state agencies (*51*), it may be acceptable in areas where line-of-sight is not a major

Month 0 Month 2

Figure 2.8 Photographic comparison of an herbicide treatment at Month 0 and Month 2. Pictures are at the same location two months apart. Left: Month 0 (prior to herbicide application) area contained large percentage of broadleaf weeds prior to herbicide application. Right: Month 2 (2 months after application) original broadleaf cover greatly reduced with broadleaf cover <1%.

Figure 2.9 Photograph of an herbicide treatment showing the continued broadleaf control at Month 12. The black line represents the edge of the spray pattern. The area to the left of the black line is still free of broadleaves one year after herbicide application, while large populations of broadleaves can be seen to the right of the line in an area that received no herbicide.

safety concern and broadleaf weeds have been controlled.

Overall, if vegetation managers desire to cut costs, the main goal should be reduction of mowing cycles. Steps to achieve this goal include:

1. focus on eliminating broadleaf weeds through broadleaf control herbicide
2. delay the first mowing cycle until after grass has gone to seed
3. reduce the number of standard annual mowing cycles
4. mow only areas that require height management for safety
5. reduce full-width mowing
6. use PGR when additional grass regulation is needed

Figure 2.10 Photographs of research plots at Month 24. Herbicide treatment still has minimal broadleaf weeds while the mowing treatment has a large percentage of broadleaf weeds.

Figure 2.11 Photographic comparison of grass height in PGR treatment (left) and control plot without PGR (right) at 1 Month. These photographs are from another roadside management study on the effect of Plateau with no additional broadleaf herbicide application.

3. NATIVE SPECIES AS AN ALTERNATIVE TO TRADITIONAL NON-NATIVE ROADSIDE VEGETATION

3.1 Introduction

Over the past few decades, many transportation agencies have been moving towards native vegetation as a sustainable, environmentally suitable and cost-effective alternative to traditional roadside turf species (*65,76–80*). Transportation agencies benefiting from lowered maintenance costs can be found throughout the country (*78,79,81*). For instance, Iowa's program for roadside prairie establishment and restoration (*41*) has led to a 70% to 90% reduction in herbicide cost, as well as decreased costs for mowing and brush control (*77*). Delaware has reduced annual mowing cycles from eight down to one or two through the incorporation of native meadow grasses and forbs with the Enhancing Delaware Highways program; a savings of $2610 to $3045 per acre per year (*42*). Cost benefits come from the reduction in long-term maintenance costs when utilizing native vegetation.

Native grasses and forbs are capable of tolerating a wide range of environmental conditions and are presumably adapted to the local environment. Native warm-season grasses (NWSG) make up a large component of most native plantings in the Midwest. These grasses get their name because they gain the most biomass during the hottest months of the summer, typically June through August. On the other hand, most traditional roadside turf species (e.g., fescue and Kentucky bluegrass) are cool-season grasses which grow in spring and fall but become dormant during summer months (*82*). NWSG are well adapted to high light, hot temperatures and drought conditions (*52,82*), in part due to differences in photosynthesis compared to cool-season grasses (*52*). Also, NWSG roots can extend one and a half meters (5 ft) or more into the soil to access water and nutrients that other plants cannot (*83*). Drought resistance and adaption to local environmental conditions help make NWSG a cost effective and environmentally suitable vegetation option for transportation right-of-ways.

3.1.1 Native Vegetation as Part of an IVM Plan

Like any tool in an IVM plan, the success of planting native species requires knowledge of site conditions, planting limitations, and growth requirements of desired species (*84*). Soil, weather, and geology can differ drastically along short stretches of road (*80*). Even subtle differences may be important when selecting which native plants will be most successful (*34*).

Vegetation along roadside is divided into multiple management zones that run parallel to the road; each having different growing conditions and requirements for safety and maintenance. The shoulder or clear zone of a roadside includes vegetation at the edge of the pavement that must be kept short for the safety of motorists and maintenance operators. Next to the shoulder lies the ditch zone that collects runoff, followed by the backslope that adjoins the right-of-way to neighboring properties (*77*). The shoulder often contains the weediest species that are able to tolerate the continuous disturbance from both maintenance and traffic (*34*), and often has poor soil and growing conditions. The shoulder and backslope tend to dry out during the summer, and thus require the most drought tolerant plants. Ditches, on the other hand, often contain species that can handle being partially submerged in water for at least part of the year (*83*).

Because these zones have different environmental conditions (e.g., soil type and climate), they require different management techniques (*80*), and provide suitable habitat for different species (*83*). Selecting the proper species for different zones on the roadside will help provide the best complex of vegetative cover and the most success managing against weed invasion. Once established, native species require little upkeep, which reduces the need for roadside mowing and herbicide.

3.1.2 Environmental Benefits

According to the Federal Highway Administration, native plant communities are often the best defense against invasive plants, reducing both the management and environmental concerns associated with these weeds (*85*). Such concerns include high maintenance costs, invasive weed encroachment into surrounding natural areas, or misapplication of herbicide. The shorter root systems of exotic grasses conventionally planted on roadside are thought to have led to erosion and sediment loading. The longer root systems of many native species, on the other hand, can mitigate these issues, as well as improve soil and water quality (*85*).

Native roadside plantings can create insect (*37,38*) and wildlife habitat (*6,40*), and create corridors connecting fragmented habitats (*6,39*) that allow plants, insects and wildlife to disperse between areas that would have otherwise been cut off from each other. Although, increased animal habitat near roadside may cause concerns for motorist safety, studies have shown that tall vegetation and reduced mowing do not increase deer-vehicle collisions (*86*). In fact, continual mowing may increase vegetation palatability (*87,88*). Therefore, increasing native vegetation and reducing mowing may actually decrease deer foraging near road edges.

3.1.3 Objectives

The Indiana Department of Transportation (INDOT) has incorporated native plantings into their right-of-ways. The Hoosier Roadside Heritage Program is a cooperative program of the Federal Highway Administration, Department of Natural Resources, and Department of Environmental Management (*44*). This program has planted native grasses and forbs on over 800 acres of roadside since it was started in the late 1990s (*45*). Many other state transportation agencies are also preserving existing remnant prairies or incorporating new native vegetation into their IVM programs. Some of these states include Texas (*81,89*), Pennsylvania (*90*), Wisconsin (*80*), Iowa (*91*), California (*83*), West Virginia (*78,92*), Virginia (*93*), and Minnesota (*8*). These native planting projects differ greatly by location, planting densities, planting techniques, preparation and management, as well as their ultimate success.

The development of recommended planting procedures specific to Indiana, with an associated IVM plan, would benefit INDOT's long-term roadside management goals. In this study, native species mixes were planted on Indiana roadsides and their establishment and growth were assessed. The primary goal was to provide information that could lead to reductions in maintenance costs, enhance roadside aesthetics, and reintroduce native species into the landscape. The specific objectives of this research were to:

1. Assess the establishment success of four native planting treatments on INDOT-managed roadside. These treatments were western wheatgrass only (T1), a tall prairie grass mix (T2), a short prairie grass mix (T3), and a mix of short grass and forbs (T4). Determination of successful planting was based on percent cover of planted species and plant density at or above the designated success threshold for one year old plantings as suggested by the USDA Natural Resource Conservation Service (NRCS), university extension publications, and other land management reports. It was predicted that the western wheatgrass-only treatment (T1) would reach the greatest plant density during the one-year time frame of this study. Western wheatgrass is commonly used in mitigation because it establishes quickly. It was also the only cool-season grass in our study. While warm season grasses offer many benefits, they tend to establish more slowly than cool-season grasses.
2. Evaluate how site conditions (e.g., climate, weed presence, and soil) affect establishment success of the treatments. It was predicted that the longer growing season in the southern region of the state would result in a higher density of established native species than found at northern sites. Similarly, it was predicted that southern sites would also have the greatest overall vegetative cover, including weeds and other unplanted species. Finally, it was predicted that sites with high nitrogen content or those high in silt and clay would have greater establishment of planted species.
3. Evaluate native planting costs and potential savings from an IVM planting plan based on INDOT management costs.

3.2 Methods

3.2.1 Site Selection

Native plantings were installed at six sites throughout the state of Indiana; one in each INDOT district (Figure 3.1). Sites were distributed latitudinally and longitudinally to identify regional differences in treatment success due to climate or competition with weedy species. A total of 15 acres (6 hectares) were planted across the state, with individual sites ranging from 1.7 to 3.2 acres (0.7 to 1.3 hectares). Sites were located in medians, intersections, interchanges, and other large, level sections of right-of-way. All of the plantings were located beyond the shoulder and ditch area to provide safe access during planting and data collection.

3.2.2 Site Preparation and Planting

To prepare sites for planting, we attempted to kill existing plant species in order to facilitate establishment of the planted species by reducing competition for resources. On two dates, existing vegetation was sprayed with a broadcast application of glyphosate at a rate of two quarts per acre (5.6 L/ha), with 0.25% by volume Invade 90 non-ionic surfactant. Application occurred in May 2011, and again at time of planting in late June 2011. No further vegetation management occurred until after final data collection in July 2012. At that time, management was handed over to individual INDOT districts.

Planting occurred during the last week of June 2011. Planting had been scheduled for May, but this was delayed by heavy rains and flooding. All planting was done with a Truax Flex II Drill that was calibrated to ensure proper seeding depths and rates as defined by the Truax Company.

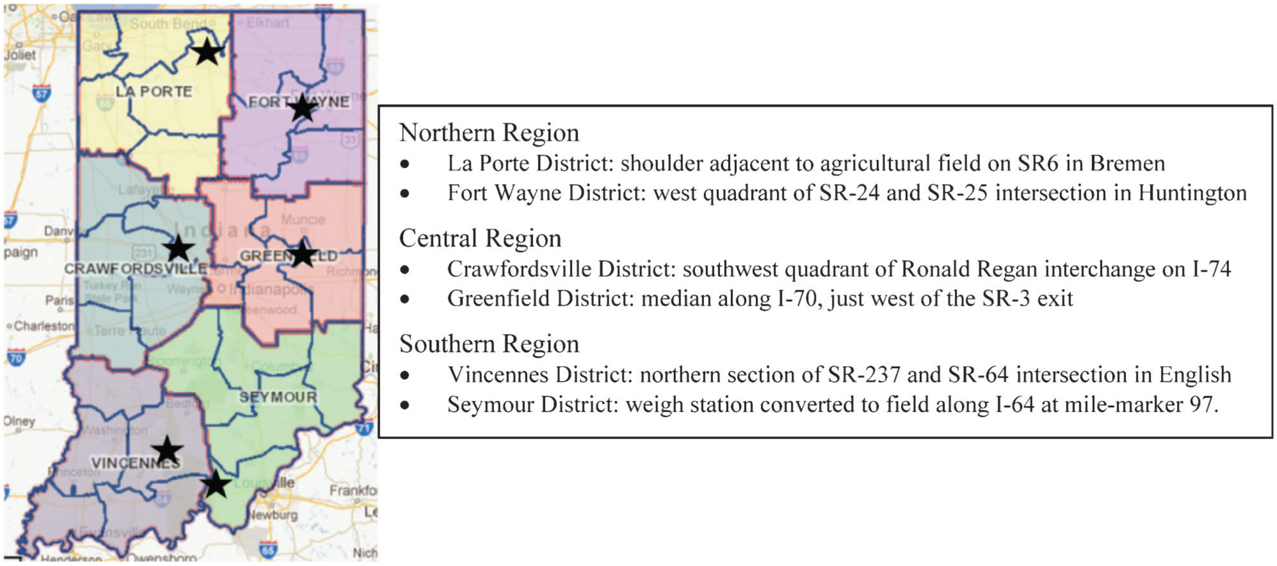


Figure 3.1 Map of the six treatment sites (black stars) and the corresponding INDOT districts (colored areas).

3.2.3 Treatments

Four treatments were studied (Table 3.1); each treatment was replicated three times at each site. Native species selection and seeding density (i.e., planting rate) for each treatment were based on seed costs, seed availability and suggestions from vegetation managers. Densities of individual species were selected to give each treatment a density of 30 seeds per square foot (98 seeds/m^2); T4 was the exception with 28 seeds per square foot (92 seeds/m^2).

3.2.4 Vegetation Inventories

Vegetation inventories were conducted three months after planting (September 2011) and one year after planting (July 2012). Five permanent sampling points were established within each plot. The number of individual plants for each native species was recorded for each species rooted within a 1-m^2 hoop placed at each sample point. The maximum height and a visual estimate of percent cover were also recorded for all species present in the sample points. Planting sites were evaluated by the percent cover of the following categories:

- Native species: this category included all species that were in any of the native planting treatment mixes. In a few instances, native species from one treatment were found within a different treatment. This may have been a result of seed dispersal from germinated plants.
- Weeds: this category included any species not found in the planting treatment mixes. Some non-planted species found at the sites were problematic invasive species that would require weed management (e.g., Canada thistle) while others would likely be acceptable in a roadside planting (e.g., fescue). Since this study focuses on how well the native species established and competed, all non-planted species were grouped together as 'weeds'.
- Bare ground: a visual estimate of the percent of ground that had no vegetation.

3.2.5 Soil Sampling

Soil samples were collected with a one-inch diameter soil corer and slide hammer, to a depth of 15 cm or reasonable rejection (i.e., the depth at which the soil corer was no longer capable of deeper penetration). Three samples were taken at each site. These samples were used to determine the concentrations of carbon and nitrogen in the soil, as well as soil texture.

3.3 Results

Density of native species (both percent cover and number of individual native plants) was lower than desired at three months after planting (end of the growing season in September 2011) and one year after planting (July 2012). Bare ground was prevalent during the 2011 season but was filled in by weeds the following season.

3.3.1 Three Months After Planting

At the end of the first growing season, the majority of the research area was bare ground (81%), followed by weeds (17%), and then by native species (2%). T4 had the greatest cover of planted species out of all treatments. The Fort Wayne District had the highest cover of planted species of all sites, having at least twice as much as any other site. The amount of bare ground and weed species varied between sites (Figure 3.2).

3.3.2 One year After Planting

The majority of the research area was weeds (65%), followed by bare ground (29%), and then native species (6%). Weeds were the main concern at plantings sites with five of the six sites having over 60% cover of weed species (Figure 3.2). The weediest treatment varied by

TABLE 3.1
Species, seeding density, and planting cost for native planting treatments.*

Treatment		Seeding Density		Cost	
		seed/ft² (seed/m²)	PLS-lb/ac (PLS-kg/ha)	$/PLS-lb ($/PLS-kg)	$/ac ($/ha)
T1: Western Wheatgrass					
western wheatgrass	*Pascopyrum smithii*	30 (98)	11.9 (13.1)	5.00 (11.02)	59.50 (147.02)
Totals		**30 (98)**	**11.9 (13.1)**		**59.50 (147.02)**
T2: Tall Grass Mix					
big bluestem	*Andropogon gerardii*	6 (20)	2.0 (2.2)	8.00 (17.64)	16.00 (39.54)
Indiangrass	*Sorghastrum nutans*	6 (20)	1.5 (1.7)	8.00 (17.64)	12.00 (29.65)
little bluestem	*Schizachyrium scoparium*	9 (30)	1.5 (1.7)	10.00 (22.05)	15.00 (37.07)
switchgrass	*Panicum virgatum*	6 (20)	0.9 (1.0)	5.55 (12.24)	5.00 (12.36)
western wheat	*Pascopyrum smithii*	3 (10)	1.2 (1.3)	5.00 (11.02)	6.00 (14.83)
Totals		**30 (98)**	**7.1 (7.8)**		**54.00 (133.44)**
T3: Short Grass Mix					
little bluestem	*Schizachyrium scoparium*	9 (30)	1.5 (1.7)	10.00 (22.05)	15.00 (37.07)
sideoats grama	*Bouteloua curtipendula*	9 (30)	2.1 (2.3)	9.50 (20.94)	19.95 (49.30)
buffalograss	*Bouteloua dactyloides*	1 (3)	0.8 (0.9)	12.75 (28.11)	10.20 (25.20)
sand dropseed	*Sporobolus cryptandrus*	8 (26)	0.1 (0.1)	6.50 (14.33)	0.65 (1.61)
western wheat	*Pascopyrum smithii*	3 (10)	1.2 (1.3)	5.00 (11.02)	6.00 (14.83)
Totals		**30 (98)**	**5.7 (6.3)**		**51.80 (128.00)**
T4: Short Grass/Forb Mix					
little bluestem	*Schizachyrium scoparium*	9 (30)	1.5 (1.7)	10.00 (22.05)	15.00 (37.07)
sideoats gramma	*Bouteloua curtipendula*	9 (30)	2.1(2.3)	9.50 (20.94)	19.95 (49.30)
lupine	*Lupinus perennis*	1 (3)	1.9 (2.1)	42.50 (93.70)	81.60 (201.64)
purple prairie clover	*Dalea purpurea*	1 (3)	0.2 (0.2)	25.50 (49.60)	3.83 (9.46)
black eyed susan	*Rudbeckia hirta*	1 (3)	0.1 (0.1)	18.75 (41.38)	0.56 (1.38)
sky blue aster	*Aster oolentangiensis*	1 (3)	0.3 (0.3)	198.00 (436.50)	67.32 (166.35)
purple coneflower	*Echinacea purpurea*	1 (3)	0.3 (0.3)	23.00 (50.71)	8.28 (20.46)
plains coreopsis	*Coreopsis tinctoria*	1 (3)	0.1 (0.1)	18.00 (39.68)	0.54 (1.33)
partridge pea	*Chamaecrista fasciculata*	1 (3)	0.7 (0.8)	14.25 (31.42)	9.98 (24.66)
lanceleaf coreopsis	*Coreopsis lanceolata*	1 (3)	0.2 (0.2)	26.25 (57.87)	5.80 (14.33)
blanket flower	*Gaillardia aristata*	1 (3)	0.3 (0.3)	26.50 (58.42)	8.75 (21.62)
Illinois bundle flower	*Desmanthus illinoensis*	1 (3)	0.5 (0.6)	21.00 (46.30)	10.71 (26.46)
Totals		**28 (92)**	**8.2 (9.0)**		**232.32 (574.08)**

*Seeding density given in seeds per square foot (seed/ft²) and pounds of pure live seed per acre (PLS-lb/ac). Costs per pound of pure live seed ($/PLS-lb) and cost of seed per acre ($/acre). Metric measurements given in parenthesis.

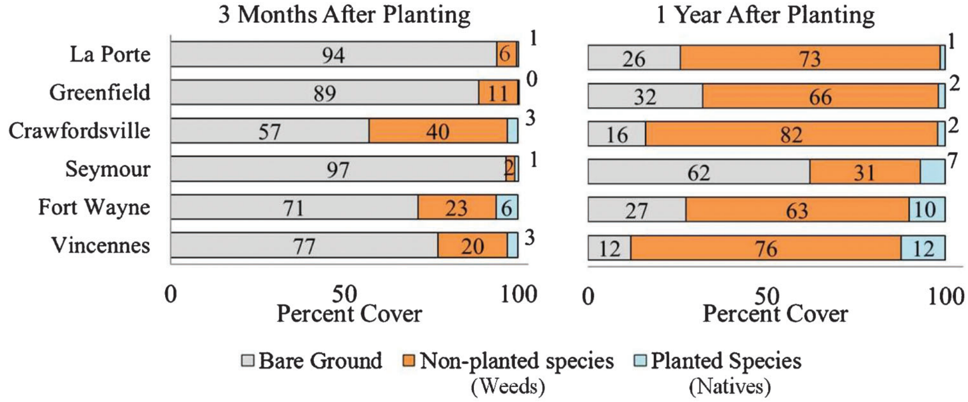


Figure 3.2 Mean percent cover of bare ground, weed species and native species for individual sites at three months after planting (September 2011) and one year after planting (July 2012).

site and therefore no treatment consistently performed better at preventing weed emergence.

Native species were analyzed based on both percent cover (Figure 3.2 and Figure 3.3), as well as the number of individual native plants that sprouted (Table 3.2). Sites showed differences in overall success of plantings. The percent cover of native species was highest in Vincennes, Fort Wayne and Seymour (7–12%; Figure 3.2). As would be expected, these three sites also had the greatest number of native plants (Table 3.2a). Differences in treatments were also apparent. T4 and T1 had the greatest percent native cover with an average of 10% and 7% across all sites (Figure 3.3 insert), but the treatment with the greatest native species cover varied by site (Figure 3.3). Forbs were responsible for the majority of the native percent cover in T4; however, this was due to the large amount of forb cover in the Fort Wayne and Vincennes sites.

When comparing the number of individual native plants that sprouted in each treatment, T1 was the most successful treatment (2.9 plants/m^2) followed by T4 (1.8 plants/m^2). T1 therefore had more native plants sprout, but T4 covered a greater area due to the large area an individual forb plant occupies compared to that of a grass plant. Site differences were also seen in individual native species including western wheatgrass, little bluestem, Indiangrass, lanceleaf coreopsis, partridge pea, and blanket flower (Table 3.2b).

3.3.3 Soil Texture, Carbon and Nitrogen

Soil carbon and nitrogen concentration, as well as the ratio of carbon to nitrogen (C:N) differed among sites (Table 3.3). However, none of these differences were predictors of native plant density, weed density, total vegetation, or bare ground. Although the two sites with the greatest native plant density also had the highest nitrogen concentrations, Seymour had the third highest native density but the lowest nitrogen concentration. Therefore no relationship between nitrogen concentration and native plant density was seen in this study.

Planting sites were on loam, silt loam, and loamy sand. Of the soil texture variables, percent silt was the only predictor of native plant density, including the number of natives and native percent cover. Sites with the highest native density were all silt loam soils; however, percent silt ranged from 31.2% to 47% at those sites.

3.4 Discussion

The objectives of this study were to assess the establishment of the native planting treatments on INDOT roadside, evaluate how site growing conditions affected these treatments, and evaluate planting costs. Overall, native plantings were less successful than expected, with only one of the treatments, and only two of the sites exceeding the lowest of the seedling density thresholds suggested for establishment. Two years of drought along with inadequate weed control likely contributed to the low establishment. Suggested native plant density needed for a successful native warm season grass stand vary, but it is generally accepted that two healthy plants per square foot (20/m^2) will lead to a successful stand in the majority of cases (*94–96*). One plant per square foot (10/m^2) may also be considered successful (*95,97*), while one plant per two square feet (5/m^2) will likely succeed but may need to be replanted (*97*). According to the USDA Natural Resource Conservation Service (NRCS) webpage on Establishment and Management of Native Prairie, a minimum of 0.25 seeded plants per square foot (2.7/m^2) can be considered a successful prairie planting but notes that prairies may take two to five years to establish. With an overall average native plant density of less than 2/m^2 in July the year after planting, few of our treatments or sites met the threshold to be deemed successful plantings. However,

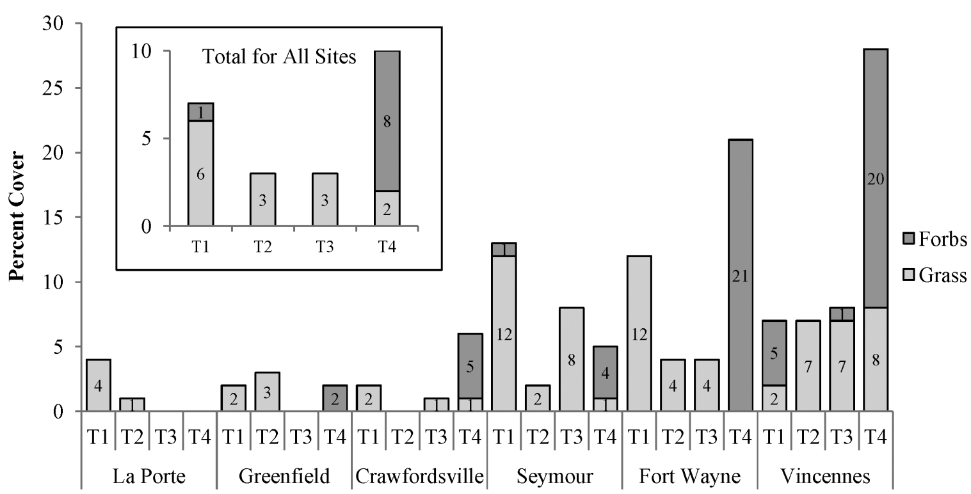


Figure 3.3 Mean percent cover of native grass and native forbs by treatment and site at one year after planting (July 2012). T1 = only western wheatgrass, T2 = tallgrass mix, T3 = shortgrass mix and T4 = shortgrass with forb mix. Insert is the average percent cover of native species for each treatment.

TABLE 3.2
Average number of native plants per square meter (plants/m^2) one year after planting (July 2012) for (a) treatments and sites (b) individual species within treatments.*

(a)

	C	F	G	L	S	V	Mean
T1	1.06	**5.73**	**2.66**	2.47	**4.07**	1.40	**2.90**
T2	0.0	1.80	2.13	0.27	0.60	1.33	1.02
T3	0.07	1.13	0.20	0.07	**2.87**	**2.93**	1.21
T4	1.20	2.33	0.26	0.20	1.00	**5.73**	1.79
Mean	0.58	**2.75**	1.31	0.75	2.13	**2.85**	

(b)

		District Sites					
Species by Treatment		**C**	**F**	**G**	**L**	**S**	**V**
T1	western wheatgrass	1.06	5.73	2.66	2.40	4.00	1.01
	lanceleaf coreopsis	—	—	—	0.07	—	—
	partridge pea	—	—	—		0.07	—
	little bluestem	—	—	—		—	0.07
	black-eyed Susan	—	—	—		—	0.20
T2	western wheatgrass	—	0.47	2.13	0.13	0.40	0.07
	little bluestem	—	1.20	—	0.13	0.20	0.73
	indian grass	—	0.07	—	—	—	0.53
	switchgrass	—	0.07	—	—	—	—
T3	western wheatgrass	0.07	0.93	0.13	—	0.73	0.13
	sand dropseed	—	0.02	0.0[a]	—	—	—
	little bluestem	—	—	0.07	0.07	0.07	1.07
	sideoats grama	—	—	—	—	0.07	1.53
	buffalograss	—	—	—	—	0.93	0.07
	black-eyed Susan	—	—	—	—	—	0.07
	IL Bundle Flower	—	—	—	—	—	0.07
T4	western wheatgrass	0.07	—	—	—	—	—
	little bluestem	0.13	—	—	0.07	0.27	2.33
	sideoats grama	0.13	—	—	—	0.13	0.20
	black-eyed Susan	0.27	0.53	0.07	—	—	—
	Illinois bundle flower	0.47	0.13	—	—	—	0.47
	lanceleaf coreopsis	0.13	0.93	—	—	—	0.07
	switchgrass	—	0.07	—	—	—	—
	partridge pea	—	0.27	—	—	0.60	2.47
	blanket flower	—	0.40	0.20	—	—	0.07
	perennial lupine	—	—	—	0.13	—	0.07
	Purple prairie coneflower	—	—	—	—	—	0.07

***Bold numbers** indicated treatments, sites, or treatments within sites that were successful based on the desired threshold of 2.7 plants/m^2. *Italized species* were those found that were not planted within that particular treatment. District site abriviations: C=Crawfordsville, F=Fort Wayne, G=Greenfield, L=La Porte, S=Seymour, and V=Vincennes.

there was some indication that all treatments continued to improve beyond that time at some of the sites.

3.4.1 Treatment Establishment

As predicted, the western wheatgrass-only treatment (T1) had the highest density (number of individual plants) of planted species of all the treatments. With an average of 2.9 plants per square meter, T1 was the only treatment to meet establishment guidelines; however, it was only successful based on the lowest establishment threshold of 2.7 plants per square meter set by the NRCS. Only six of the treatments at individual sites were above the NRCS density threshold (T1 in Greenfield, Fort Wayne, and Seymour, T3 in Seymour and Vincennes, and T4 in Vincennes), two of which were also above the five plants per square meter threshold (T1 in Fort Wayne and T4 in Vincennes).

Low cover of native species during the first or second season of planting is not uncommon in native planting studies (*79,80*). In the Midwest, native warm season prairie grasses direct most of their energy into extensive root systems during the first growing season. This investment in root systems helps increase drought tolerance (*83*), but delays the establishment of above ground shoots, leading to sparse cover of native vegetation during the first two years. For this reason, plantings may appear to have failed during their first or second growing season, but usually exhibit a substantial increase in cover by the third year (*20,43,78,79,90,98*).

The low density of our plantings in the year following planting suggests that most sites and treatments are not likely to develop into successful native plant stands. However, informal visual observations during the third growing season suggest that that some sites are now successful; in particular the Fort Wayne site. A couple things can be taken away from this: native planting studies need to be followed into the third growing season or longer, and further study of establishment, planting density and management are needed for plantings that occur in drought years.

TABLE 3.3
Soil qualities for each of the six planting sites.*

Site	C	N	C:N	Texture (Sand/Silt/Clay)
La Porte	1.77	0.13	11.19	Loamy Sand (73.2/26.0/0.8)
Fort Wayne	2.66	0.22	9.75	Silt Loam (31.2/62/6.8)
Crawfordsville	2.03	0.10	13.74	Loam (43.2/44.0/12.8)
Greenfield	3.52	0.13	12.10	Loam (43.2/40.0/16.8)
Seymour	0.53	0.04	21.84	Silt Loam (31.2/50.0/18.8)
Vincennes	1.77	0.17	32.50	Silt Loam (47.2/50.0/2.8)

*Including average carbon (C), and nitrogen (N) concentration, carbon to nitrogen ratio (C:N), texture, and percent sand, silt and clay.

3.4.2 Growing Condition/Site Differences

The only sites with average native plant densities above the 2.7 plants per square meter suggested by the NRCS were Fort Wayne (2.75 plants per square meter), and Vincennes (2.85 plants per square meter). Many factors influenced the success of our native plantings, including growing conditions during the first year, site preparation and site characteristics. Understanding how each of these influence the potential success of a planting site is an important part of IVM.

3.4.2.1 Climate. Indiana, stretching 280 mi (451 km) from north to south, has a gradient of climate conditions (growing season length, temperature, and precipitation) from the northern to the southern portion of the state. The growing season in Indiana ranges from 155 days in the northern part of the state to 185 days in the south. Because warm season grasses take longer to establish, it was predicted that the longer growing season in the south would lead to higher native plant density. Although the two southern sites had the first- and third-greatest native plant density, the northern Fort Wayne site had the second greatest.

Water availability is one of the most important factors determining plant cover and composition (*83*). Although drought tolerant, native grasses still require adequate soil moisture in order to successfully establish from seed. Weather conditions in 2011 and 2012 were not favorable for plant establishment throughout the whole state, making it difficult to assess regional differences. Planting dates were originally scheduled for May in order to provide a longer growing period during the first year of planting; however, heavy rains and flooding delayed planting till the last week of June 2011. Subsequently, in July 2011, there was a severe drought, with less than 50% of the normal annual precipitation during the rest of the growing season. Therefore, seedlings likely did not get the adequate moisture needed to germinate, or germinated and then died. A second year of drought, with rainfall below 25% of normal during the first several months of the 2012 growing season, further limited growth.

Drought has been documented as a contributing factor in other native roadside plantings that resulted in low plant density. A native roadside study planted during a two-year drought in Wisconsin grew little during the first years (*80*). Five years after planting, cover in the plots remained below 50%, but had continued to increase every year. Out of the twenty-two species planted in the Wisconsin study, little bluestem, side oats, black-eyed Susan, lance-leaf coreopsis and coneflower did well, while purple prairie clover, sky blue aster and Indian grass were not successful. In comparison, the most successful species for our study were western wheatgrass, little bluestem, sideoats grama, black-eyed Susan, Illinois bundle flower, lanceleaf coreopsis and partridge pea, while purple prairie clover, sky blue aster and Indian grass were not (Table 3.2).

3.4.2.2 Weeds. It was predicted that southern sites would have the greatest cover of weed species since the growing season in the southern portion of the state may allow more time for weed species to re-emerge after herbicide application. While weedy species were prevalent at all of our sites the year after planting, the cover of weed species varied between the two southern sites. Vincennes had the second-greatest percent cover while Seymour had the least cover of weed species (Figure 3.2). Because native species take time to establish, native planting sites can be overrun with invasive species and other early successional weeds that compete for nutrients, water and light. Poor preparation leads to an abundance of weeds that must be managed after planting (*83*) and is cited as a reason for limited success in other studies (*80*).

All of the sites would have benefited from more site preparation. Deep thickets of dead plants increased the difficulty of drilling seeds into the soil in some areas and required planting depth adjustments to compensate. The abundant plant litter at the time of planting likely decreased light availability for the new seedlings and prevented some precipitation from reaching the soil, potentially intensifying effects of the drought on soil moisture.

Sites were prepared for planting with herbicide in a similar manner to that used successfully in other native planting studies (*83,93*). This shows that site-by-site evaluation is needed before planting begins. While our two rounds of herbicide application might have been successful under some conditions, they were not adequate at the sites we used. Site preparation options other than herbicide exist. Some studies suggest tilling or disking prior to planting as a useful tool to bury weeds (*83*). Others studies advise against these methods because they disrupt the soil, potentially cause more weeds to germinate, increase erosion, deplete soil moisture, and remove organic matter (*84*). Planting in the fall also may help natives compete with weedy vegetation (*83*).

3.4.2.3 Soil. It was predicted that sites with the highest silt and clay content, as well as those with the highest nitrogen concentration would have the most native species; however, neither of these qualities determined vegetative cover of natives, weeds, or total vegetation. Sites with the highest native density were all silt loam soils, and percent silt was the only soil characteristic that was a predictor for native establishment, with higher silt percentages correlating with higher native plant density. Although there was no correlation between nitrogen and native plant density, the two sites with high nitrogen content had the greatest density of native species. The high nitrogen content at Fort Wayne and Vincennes suggests that they had fertile soil which likely contributed to their relatively high native plant density. The Seymour site had the lowest soil nitrogen content of any site (Table 3.3) suggesting lower soil fertility. This may help explain why the Seymour site had twice as much bare ground of any other site. However, while the Seymour site had less overall vegetative cover (native and weed species), it had the third-greatest density of native species.

3.4.2.4 Management Zones. Although all seed mixes were planted within the backslope zone, some of the seed mixes would likely be appropriate for different zones (Figure 3.4). For instance, western wheatgrass and the short grass mix could be appropriate for shoulders as they are shorter species and would present little visual restriction. Western wheatgrass establishes quickly on degraded sites and is therefore commonly used for erosion control and reclamation. Forbs should

Figure 3.4 Selection of native grass treatments for different management zones as described in section 3.4.2.4.

be planted were they offer the most aesthetic appeal. Tall grass species could be planted further away from the road edge, so that they did not block line-of-sight, or could be utilized as a visual barrier (i.e., in medians) when beneficial.

3.4.3 Cost Analysis

Seed costs for the three grass-only mixes (T1–T3) were fairly comparable, ranging from \$128 to \$133/ha (\$52/acre to \$60/acre) (Table 3.1). T1 was the only treatment to meet the suggested plant/m^2 density threshold, and therefore offered the best establishment for the cost. However, informal visual observations in the third growing season suggest that T2 and T3 may also have a high enough plant density to be deemed successful at a few sites, especially at the Fort Wayne District site. Future vegetation inventories will be necessary and may change grass treatment cost assessments.

The short grass and forb treatment (T4) cost approximately four times more than any of the grass-only treatments (Table 3.1). Although the forb treatment had the greatest overall percent cover of any treatment (Figure 3.3), it had only the second greatest plant density. In addition, based on density thresholds, forbs were only successful at the Vincennes site and marginally successful at the Fort Wayne District site (Figure 3.3). Partridge pea, lance-leaf coreopsis, and Illinois bundle flower were the most successful species. The most expensive species, sky blue aster, was not found during vegetation inventories. The second most expensive, perennial lupine, was recorded but its presence was much lower than other less expensive species. Therefore we would suggest limiting use of these species unless other field tests suggest they would succeed in the desired area.

Although not part of our study, another area near the research plots deserves discussion. A forb seed mix was planted (including some of the same forb species as T4) at high density in areas bordering the experimental plots at the Vincennes District site in order to enhance aesthetic appeal since this site was in public view. Exact seeding density was not calculated because these borders were not part of the research area, but it was at least 5 times the density of forbs in the T4 treatment. One year after planting, percent cover and plant density data were collected from five sample points within each of the four border rows. At 80% cover, density of native species in these border rows was higher than in any of the research treatment plots, suggesting that seeding densities in the treatments were too low for a drought year and should be increased in future studies. This also may suggest that dense stands of forbs provide better competion with weed species than sparse native grasses during the first few years of planting. Weed cover in border rows was only 8%. In comparision, weeds made up 69% of the T4 plots and 66% of the grass-only plots (T1–T3). The exact cost of seeding these borders is impossible to determine because the exact seed density and species is unknown. However, since the cost of T4, excluding grasses and the expensive lupine and sky blue aster species, was \$48.45/acre (\$119.70/ha) we estimate that the cost of these boarder areas was five times that cost.

The value of forbs in roadside native plantings is debated in the literature. As seen with the border areas around the Vincennes District site, forbs may offer good weed control when planted at high enough rates. However, some studies suggest not adding forbs unless they are desired aesthetically (*20*). A main concern with forbs is that their presence tends to decline over time, causing the need to replant with expensive seed (*99,100*). The addition of native forbs also limits control options such as broadcast herbicide, or these desirable forbs are ultimately killed when broadleaf weed treatments are required.

Planting costs are dependent on species and seeding density. As was done with our border areas, managers sometimes plant seeds at high densities to increase the density of germinating plants, but this also greatly increases seed costs. More research should therefore be conducted on multiple planting rates of both grasses and forbs and the resulting costs.

The cost of seeds is a main concern for many state agencies; however, in Indiana, INDOT has an in-house native seed program with three seed farms and a greenhouse (*45*), and additional seed harvesting is coordinated by the Department of Correction Works (*101*). This greatly reduces the cost of seed to the state. With over 800 acres planted since INDOT's native seed program began, plantings across the state have reduced maintenance needs according to INDOT maintenance records. One such example is wildflower plantings on the section of SR-231 between I-70 and U.S. 40. Had this area stayed on the traditional maintenance schedule, it would have likely been mowed two to three times per year. Instead, it has only needed to be mowed twice in the past eight years.

3.5 Conclusions

Two sites (Vincennes and Fort Wayne) and one treatment (T1) met the desired establishment threshold of 2.7 plants per square meter (Table 3.2). Some seed mixes performed well only at certain sites, showing the need for selecting seed mixes based on location. The highest density of native plants was seen in T1 at the Fort Wayne site, and T4 at the Vincennes site; both having above five plants per square meter. Success of certain native vegetation can be seen from photographs taken throughout the study (Figure 3.5, Figure 3.6, and Figure 3.7).

Low native density was likely the result of a combination of inadequate weed management and weather conditions. This study highlights the importance of weed management both prior to planting and during the first few years after planting. It also shows the problems associated with invasive roadside plant species. Two years of drought also decreased establishment at all of the sites. Further research into weed control methods and planting densities is needed, especially pertaining to drought years.

Figure 3.6 Photograph of T4 (short grass and forbs) one year after planting at the Vincennes District site. Forb treatments did relatively well within certain sections of Seymour and Fort Wayne Districts as well, but T4 only meet the NRCS density threshold of 2.7 plants/m^2 (as well as meeting stricter guidelines of above 5 plants/m^2) at the Vincennes District site.

Although sparse cover of native planted species may be attributed to weather and weeds, poor native cover during the first and second season is frequently reported in studies of native warm season grasses. Because natives can take three or more years to establish, these planting sites should continue to be

Figure 3.5 Photographs of T1 (western wheatgrass-only) one year after planting with clear planting rows visible. T1 had the highest native plant density and was the only treatment to meet establishment guidelines. T1 was most successful in Greenfield, Fort Wayne (top) and Seymour (bottom) Districts. The differences in weed cover is also apparent between the two pictures, with the Seymour site having more bare ground and less non-planted species.

Figure 3.7 Photograph of T3 (short grass) one year after planting at the Vincennes District site. T3 meet the NRCS density threshold of 2.7 plants/m^2 at the Vincennes and Seymour District sites.

monitored to see if native cover increases over the next few years. Although no data was collected in the 2013 growing season, visual observations suggest that establishment has increased at certain sites during the third growing season. Data collection in future years will help determine the success of these plantings.

REFERENCES

1. Venner, M. NCHRP Synthesis 341: Environmental Stewardship Practices, Procedures, and Policies for Highway Construction and Maintenance. Transportation Research Board of the National Academies, Washington, D.C., 2004.
2. Berger, R. L. *NCHRP Synthesis of Highway Practice 341: Integrated Roadside Vegetation Management*. Transportation Research Board of the National Academies, Washington, D.C., 2005.
3. Buhler, D. D. Challenges and Opportunities for Integrated Weed Management. *Weed Science*, Vol. 50, No. 3, 2002, pp. 273–280.
4. Appelt, P. J., and A. Beard. Components of an Effective Vegetation Management Program. *IEEE Rural Electric Power Conference*, Albuquerque, New Mexico, 2006, pp. 1–8.
5. Mortensen, D., L. Bastiaans, and M. Sattin. The Role of Ecology in the Development of Weed Management Systems: An Outlook. *Weed Research*, Vol. 40, No. 1, 2000, pp. 49–62.
6. Lugo, A. E., and H. Gucinski. Function, Effects, and Management of Forest Roads. *Forest Ecology and Management*, Vol. 133, No. 3, 2000, pp. 249–262.
7. Forman, R. T., and L. E. Alexander. Roads and Their Major Ecological Effects. *Annual Review of Ecology and Systematics*, Vol. 29, 1998, pp. 207–231.
8. Jacobson, R. L., N. J. Albrecht, and K. E. Bolin. Wildflower Routes: Benefits of a Management Program for Minnesota Right-of-Way Prairies. In *Proceedings of the Twelfth North American Prairie Conference*, Cedar Falls, Iowa, Aug. 5–9, 1990, pp. 153–158.
9. Valéry, L., H. Fritz, J. C. Lefeuvre, and D. Simberloff. In Search of a Real Definition of the Biological Invasion Phenomenon Itself. *Biological Invasions*, Vol. 10, No. 8, 2008, pp. 1345–1351.
10. Colautti, R. I., and D. M. Richardson. Subjectivity and Flexibility in Invasion Terminology: Too Much of a Good Thing? *Biological Invasions*, Vol. 11, No. 6, 2009, pp. 1225–1229.
11. Ross, M., and C. Lembi. *Applied Weed Science* (2nd ed.). Prentice-Hall, Upper Saddle River, New Jersey, 1999.
12. Kalwij, J. M., S. J. Milton, and M. A. McGeoch. Road Verges as Invasion Corridors? A Spatial Hierarchical Test in an Arid Ecosystem. *Landscape Ecology*, Vol. 23, No. 4, 2008, pp. 439–451.
13. Joly, M., P. Bertrand, R. Y. Gbangou, M. C. White, J. Dubé, and C. Lavoie. Paving the Way for Invasive Species: Road Type and The Spread of Common Ragweed (*Ambrosia artemisiifolia*). *Environmental Management*, Vol. Vol. 48, No. 3, 2011, pp pp. 514–522.
14. Jodoin, Y., C. Lavoie, P. Villeneuve, M. Theriault, J. Beaulieu, and F. Belzile. Highways as Corridors and Habitats for the Invasive Common Reed *Phragmites australis* in Quebec, Canada. *Journal of Applied Ecology*, Vol. 45, No. 2, 2008, pp. 459–466.
15. Mack, R. N., D. Simberloff, W. M. Lonsdale, H. Evans, M. Clout, and F. A. Bazzaz. Biotic Invasions: Causes, Epidemiology, Global Consequences, and Control. *Ecological Applications*, Vol. 10, No. 3, 2000, pp. 689–710.
16. Amor, R., and P. Stevens. Spread of Weeds From a Roadside Into Sclerophyll Forests at Dartmouth, Australia. *Weed Research*, Vol. 16, No. 2, 1976, pp. 111–118.
17. Hansen, M. J., and A. P. Clevenger. The Influence of Disturbance and Habitat on the Presence of Non-native Plant Species Along Transport Corridors. *Biological Conservation*, Vol. 125, No. 2, 2005, pp. 249–259.
18. Schooler, S. S., T. Cook, G. Prichard, and A. G. Yeates. Disturbance-mediated Competition: The Interacting Roles of Inundation Regime and Mechanical and Herbicidal Control in Determining Native and Invasive Plant Abundance. *Biological Invasions*, Vol. 12, No. 9, 2010, pp. 3289–3298.
19. Murray, B., and M. Phillips. Invasiveness in Exotic Plant Species is Linked to High Seed Survival in the Soil. *Evolutionary Ecology Research*, Vol. 14, No. 1, 2012, pp. 83–94.
20. Carpenter, P. L., and J. B. Masiunas. *Techniques to Increase Survival of New Highway Plantings (Seeding Portion)*. Publication FHWA/IN/JHRP-82/18. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana. 1982. doi: 10.5703/1288284314056.
21. Liebman, M., and E. R. Gallandt. Many Little Hammers: Ecological Management of Crop–weed Interactions. In L. E. Jackson, ed. *Ecology in Agriculture*. Academic Press, San Diego, California, 1997, pp. 291–343.
22. Masters, R. A., and R. L. Sheley. Principles and Practices for Managing Rangeland Invasive Plants. *Journal of Range Management*, Vol. 54, No. 5, 2001, pp. 502–517.
23. Hyman, W. A., and D. Vary. *NCHRP Synthesis 272: Best Management Practices for Environmental Issues Related to Highway and Street Maintenance*. Transportation Research Board of the National Academies, Washington, D.C., 1999.
24. Nowak, C. A., and B. D. Ballard. A Framework for Applying Integrated Vegetation Management on Rights-of-way. *Journal of Arboriculture*, Vol. 31, No. 1, 2005, pp. 28–37.

25. Venner, M. *NCHRP Synthesis of Highway Practice 363: Control of Invasive Species*. Transportation Research Board of the National Academies, Washington, D.C., 2006.
26. Sheley, R. L., K. M. Goodwin, and M. J. Rinella. Mowing: An Important Part of Integrated Weed Management. *Rangelands*, Vol. 25, No. 1, 2003, pp. 29–31.
27. Holt, H. A., F. Whitford, J. M. Di Tomaso, P. Northcutt, R. Dickens, J. Orr, J. McKenzie, and G. Blase. *Model Certification Training Manual for Right-of-Way Pesticide Applicators*. Purdue University Extension, West Lafayette, Indiana, 2005.
28. Zollinger, R. K., and R. Parker. Sowthistles. In R. L. Sheley and J. K. Petroff (Eds.), *Biology and Management of Noxious Rangeland Weeds*. Oregon State University Press, Corvallis, Oregon, 1990, pp. 336–349.
29. Welterlen, M. Comparative Response of Tall Fescue Roadside Turf to Plant Growth Regulators. In J. E. Kaufman and H. E. Westerdahl (Eds.), *Chemical Vegetation Management*. Plant Growth Regulator Society of America, Athens, Georgia, 1988, pp. 187–200.
30. Johnson, B. J. Response of Tall Fescue to Plant Growth Regulators and Mowing Frequencies. *Journal of Environmental Horticulture*, Vol. 11, No. 4, 1993, pp. 163–167.
31. Johnson, B. J. Response of Tall Fescue (*Festuca arundinacea*) to Plant Growth Regulators and Mowing Frequency. *Weed Technology*, 1989, Vol. 3, No. 1, pp. 54–59.
32. Jiang, H., and J. Fry. Drought Responses of Perennial Ryegrass Treated with Plant Growth Regulators. *HortScience*, Vol. 33, No. 2, 1998, pp. 270–273.
33. Branham, B., and T. Danneberger. Growth Suppression of Kentucky Bluegrass Using Plant Growth Regulators and Degree Day Application Timing. *Agronomy Journal*, Vol. 81, No. 5, 1989, pp. 749–752.
34. Karim, M., and A. U. Mallik. Roadside Revegetation by Native Plants: I. Roadside Microhabitats, Floristic Zonation and Species Traits. *Ecological Engineering*, Vol. 32, No. 3, 2008, pp. 222–237.
35. Almquist, T. L., and R. G. Lym. Effect of Aminopyralid on Canada Thistle (*Cirsium arvense*) and the Native Plant Community in a Restored Tallgrass Prairie. *Invasive Plant Science and Management*, Vol. 3, No. 2, 2010, pp. 155–168.
36. Mallik, A. U. *Restoration of Trans-Canada Highway and Secondary Roadsides, Scenic Look Out and Facility Grounds of Terra Nova National Park, Newfoundland Using Indigenous Plants.* Terra Nova National Park, Glover Town, Newfoundland, 2000.
37. Hopwood, J. L. The Contribution of Roadside Grassland Restorations to Native Bee Conservation. *Biological Conservation*, Vol. 141, 2008, pp. 2632–2640.
38. Ries, L., D. M. Debinski, and M. L. Wieland. Conservation Value of Roadside Prairie Restoration to Butterfly Communities. *Conservation Biology*, Vol. 15, No. 2, 2001, pp. 401–411.
39. Clemens, J., S. R. Swaffield, and J. Wilson. Landscape and Associated Environmental Values in the Roadside Corridor: A Selected Literature Review. *Land Environment and People Research Report*, No. 27. LeAP, Lincoln University, New Zealand, 2010.
40. Walewski, J., S. Windhager, and S. Compton. Ecosystem-based Protocols for Systematic and Roadside Development. In *ICOET 2011 Proceedings: Effective Mitigation and Costs of Impacts*. International Conference on Ecology and Transport. Seattle, Washington, August 15–21, 2011, pp. 751–760.
41. Smith, D. D. Iowa prairie: Original Extent and Loss, Preservation and Recovery Attempts. *Journal of the Iowa Academy of Science*, Vol. 105, No. 3, 1998, pp. 94–108.
42. Lucey, A., and S. Barton. Public Perception and Sustainable Management Strategies for Roadside Vegetation. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2262, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 164–170.
43. Lucey, A., and S. Barton. Influencing Public Perception of Sustainable Roadside Vegetation Management Strategies. *Journal of Environmental Horticulture*, Vol. 29, No. 3, 2011, pp. 119–124.
44. Indiana Department of Transportation (INDOT). *Hoosier Roadside Heritage Program*. undated. http://www.in.gov/indot/2583.htm. Accessed May 14, 2013.
45. Hayden, M. Amidst a Struggle Between Neat and Native, A Roadside Wildflower Program Takes Root. *Greensburg Daily*. Greensburg, Indiana, July 26, 2010.
46. DOT. *Table 1-1: System Mileage Within the United States*. United States Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, 2010. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_01.html. Accessed July 8, 2013.
47. Wilson, M. V., and D. L. Clark. Controlling Invasive *Arrhenatherum elatius* and Promoting Native Prairie Grasses Through Mowing. *Applied Vegetation Science*, Vol. 4, No. 1, 2001, pp. 129–138.
48. Hewett, D. Grazing and Mowing as Management Tools on Dunes. *Vegetation*, Vol. 62, No. 1–3, 1985, pp. 441–447.
49. Pakeman, R., and R. Marrs. The Effects of Control on the Biomass, Carbohydrate Content and Bud Reserves of Bracken (*Pteridium aquilinum (L.) Kuhn*), and an Evaluation of a Bracken Growth Model. *Annals of Applied Biology*, Vol. 124, No. 3, 1994, pp. 479–493.
50. Bobbink, R., and J. Willems. Restoration Management of Abandoned Chalk Grassland in the Netherlands. *Biodiversity and Conservation*, Vol. 2, No. 6, 1993, pp. 616–626.
51. Zartman, R. E., C. B. McKenney, D. B. Wester, R. E. Sosebee, and J. B. Borrelli. Precipitation and Mowing Effects on Highway Rights-of-way Vegetation Height and Safety. *Landscape and Ecological Engineering*, Vol. 9, No. 1, 2013, pp. 121–129.
52. Simpson M. G. *Plant Systematics*. Elsevier Academic Press, Burlington, Massachusetts, 2006.
53. Nofal, H. R., R. E. Sosebee, C. Wan, J. Borrelli, R. Zartman, and C. McKenney. Mowing Rights-of-way Affects Carbohydrate Reserves and Tiller Development. *Rangeland Ecology and Management*, Vol. 57, No. 5, 2004, pp. 497–502.
54. Borrelli, J., C. McKenney, R. Sosebee, and R. Zartman. *Rights-of-way Mowing Height Research (NTIS TX-0, 3/7-4903-2)*. Center for Multidisciplinary Research in Transportation, Texas Tech University, Lubbock, Texas, 2003.
55. Davis, T. D., E. A. Curry, and G. L. Steffens. Chemical Regulation of Vegetative Growth. *Critical Reviews in Plant Sciences*, Vol. 10, No. 2, 1991, pp. 151–188.

56. Baumgartner, J. R., K. Al-Khatib, and R. S. Currie. Survey of Common Sunflower (*Helianthus annuus*) Resistance to Imazethapyr and Chlorimuron in Northeast Kansas. *Weed Technology*, Vol. 13, No. 3, 1999, pp. 510–514.
57. Thompson, H. War on Weeds Loses Ground. *Nature*, Vol. Vol. 485, No. 7399, 2012, p. pp. 430. doi: 10.1038/485430a.
58. Legleiter, T. R., and K. W. Bradley. Glyphosate and Multiple Herbicide Resistance in Common Waterhemp (*Amaranthus rudis*) Populations from Missouri. *Weed Science*, Vol. 56, No. 4, 2008, pp. 582–587.
59. Holen, C., H. Person, B. Holder, R. Severson, and M. Halstvedt. *On-farm Cropping Trials Northwest and West Central Minnesota*. University of Minnesota Extension, Crookston, Minnesota, 2007.
60. Nuzzo, V. *Element Stewardship Abstract for* Cirsium arvense. The Nature Conservancy, Arlington, Virginia, 1997.
61. Mayer, F., H. Albrecht, and J. Pfadenhauer. The Transport of Seeds by Soil-working Implements. *Aspects of Applied Biology*, No. 51, 1998, pp. 83–89.
62. Parr, T., and J. Way. Management of Roadside Vegetation: The Long-term Effects of Cutting. *Journal of Applied Ecology*, Vol. 25, No. 3, 1988, pp. 1073–1087.
63. Barton, S., R. Darke, and G. Schwetz. *Enhancing Delaware Highways: Roadside Vegetation Establishment and Management Manual*. Deleware Department of Transportation, Dover, Delaware, 2009.
64. Walvatne, P. How MnDOT Handles IRVM Training. *Better Roads*, Vol. 66, No. 10, 1996, pp. 18–20.
65. Hill, K., R. R. Horner, R. Willard, and W. Olympia. *Assessment of Alternatives in Roadside Vegetation Management.* No. WA-RD 621.1. Washington State Department of Transportation, 2005.
66. EPA. *Pesticides: Environmental Effects*. Environmental Protection Agency, 2012. http://www.epa.gov/pesticides/ecosystem. Accessed June 12, 2013.
67. U.S.F.S. *Managing Competing and Unwanted Vegetation Methods Information Profile: Herbicides*. U. S. Forest Service, 1994. http://www.fs.fed.us/outernet/r6/nr/fid/pubsweb/94herb.pdf. Accessed April 8, 2013.
68. Lerma-García, M. J., M. Zougagh, and A. Ríos. Magnetic Molecular Imprint-based Extraction of Sulfonylurea Herbicides and Their Determination by Capillary Liquid Chromatography. *Microchimica Acta*, Vol. 180, 2013, pp. 363–370.
69. Enloe, S. F., R. G. Lym, R. Wilson, P. Westra, S. Nissen, G. Beck, et al. Canada Thistle (*Cirsium arvense*) Control with Aminopyralid in Range, Pasture, and Noncrop Areas. *Weed Technology*, Vol. 21, No. 4, 2007, pp. 890–894.
70. Jachetta, J. J., P. L. Havens, J. A. Dybowski, J. A. Dranzfelder, and C. Tiu. Aminopyralid: A New Reduced Risk Herbicide for Invasive Species Control: Toxicology, Ecotoxicology, and Environmental Fate Profile. *Western Society of Weed Science*, Vol. 58, 2005, pp. 60–61.
71. Lewis, D. Environmental Fate and Biological Impact of Aminocyclopyrachlor in Turfgrass and Neighboring Systems. PhD dissertation. North Carolina State University, Raleigh, North Carolina, 2012.
72. Bell, J. L., I. C. Burke, and T. S. Prather. Uptake, Translocation and Metabolism of Aminocyclopyrachlor in Prickly Lettuce, Rush Skeletonweed and Yellow Starthistle. *Pest Management Science*, Vol. 67, No. 10, 2011, pp. 1338–1348.
73. Boydston, R. A. Soil Water Content Affects the Activity of Four Herbicides on Green Foxtail (*Setaria viridis*). *Weed Science*, Vol. 38, No. 6, 1990, pp. 578–582.
74. Stewart, C. L., R. Nurse, A. Hamill, and P. Sikkema. Precipitation Influences Pre- and Post-Emergence Herbicide Efficacy in Corn. *American Journal of Plant Science*, Vol. 3, No. 9, 2012, pp. 1193–1204.
75. Ahmadi, M., L. Haderlie, and G. Wicks. Effect of Growth Stage and Water Stress on Barnyardgrass (*Echinochloa crus-galli*) Control and on Glyphosate Absorption and Translocation. *Weed Science*, Vol. 28, No. 3, 1980, pp. 277–282.
76. Egan, D., and J. A. Harrington. Use of Native Vegetation in Roadside Landscaping: A Historical Review. In *Proceedings of the Twelfth North American Prairie Conference.* Cedar Falls, Iowa. August 5–9, 1990, pp. 147–151.
77. Quarles, W. Native Plants and Integrated Roadside Vegetation Management. *IPM Practitioner*, Vol. Vol. 25, No. 3–4, 2003.
78. Skousen, J., and C. Venable. Establishing Native Plants on Newly-constructed and Older-Reclaimed Sites Along West Virginia Highways. *Land Degradation and Development*, Vol. 19, No. 4, 2008, pp. 388–396.
79. Skousen, J., and R. Fortney. Initial Results of Native Species Establishment on Highway Corridors in West Virginia. *American Society of Mining and Reclamation*, 2003, pp. 1172–1185.
80. Harrington, J. A. Planning and Implementation of a Right-of-Way Native Planting for Wisconsin Highway 51. In *Proceedings of the North American Prairie Conference*. College of Biological Sciences, Ohio State University, 1995, p. pp. 175.
81. Tinsley, M. J., M. T. Simmons, and S. Windhager. The Establishment Success of Native Versus Non-native Herbaceous Seed Mixes on a Revegetated Roadside in Central Texas. *Ecological Engineering*, Vol. 26, No. 3, 2006, pp. 231–240.
82. de Koff, J. P. *Native Warm-Season Perennial Grasses for Drought Management in Forage Production*. ANR-B2. Tennessee State University Cooperative Extension Program, 2013.
83. O'Dell, R., S. Young, and V. Claassen. Native Roadside Perennial Grasses Persist a Decade After Planting in the Sacramento Valley. *California Agriculture*, Vol. 61, No. 2, 2007, pp. 79–84.
84. Parrish, D. J. *Roadside Flower Research: No-Till Planting*. Annual Report October 2002 to June 30, 2003. Virginia Department of Transportation, Virginia Tech, 2003.
85. Steinfeld, D. E., S. A. Riley, K. M. Wilkinson, T. D. Landis, and L. E. Riley. *A Manager's Guide to Roadside Revegetation Using Native Plants*. FHWA-WFL/TD-07-006. Federal Highway Administration, Washington, D.C., 2007.
86. Barnum, S., and G. Alt. Effect of Reduced Roadside Mowing on Rate of Deer-Vehicle Collisions. Paper #13-5041. In *Proceedings of Transportation Research Board 92nd Annual Meeting*. Transportation Research Board of the National Academies, Washington, D.C., 2013.
87. Mastro, L. L., M. R. Conover, and S. N. Frey. Deer–vehicle Collision Prevention Techniques. *Human-Wildlife Conflicts*, Vol. 2, No. 1, 2008, pp. 80–92.
88. Knapp, K. K., X. Yi, T. Oakasa, W. Thimm, E. Hudson, and C. Rathmann. *Deer-vehicle Crash Countermeasure Toolbox: A Decision and Choice Resource*. Midwest Regional University Transportation Center, Deer-

Vehicle Crash Information Clearinghouse, University of Wisconsin-Madison, 2004.
89. Markwardt, D. Texas Roadside Wildflowers. *Native Plants Journal*, Vol. 6, No. 1, 2005, pp. 69–71.
90. Johnson, J. M., K. L. Lloyd, J. C. Sellmer, and A. E. Gover. *Roadside Vegetation Management Research–2010 Report*. No. PA-201-005-PSU-016. The Thomas D. Larson Pennsylvania Transportation Institute, 2010.
91. Landers, R. The Use of Prairie Grasses and Forbs in Iowa Roadside and Park Landscapes. In *Proceedings of the Second Midwest Prairie Conference.* U.W. Madison and U.W. Parkside. Sept. 18–20, 1970, pp. 180–183.
92. Wennerberg, S. B., D. I. Ford-Werntz, J. B. McGraw, and W. N. Grafton. Propagation and Field Assessment of West Virginia Native Species for Roadside Revegetation. PhD dissertation. West Virginia University, 2005.
93. Booze-Daniels, J., W. Daniels, R. Schmidt, J. Krouse, and D. Wright. *Establishment of Low Maintenance Vegetation in Highway Corridors: Reclamation of Drastically Disturbed Lands.* American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc., Madison, Wisconsin, 2000, pp. 887–920.
94. Rector, B. S. *Rangeland Risk Management for Texans: Seeding Rangeland*. AgriLIFE Extention Texas A&M System. E-117 10-00, undated. http://hdl handle net/1969. 2000;1:86954. Accessed Oct. 14, 2013.
95. Dickerson, J. A., B. Wark, D. Burgdof, R. Maher, A. Bush, W. Poole, and C. Miller. *Vegetating with Native Grasses in Northeastern North America*. USDA-Natural Resources Conservation Service and Ducks Unlimited Canada, 1998.
96. Swartz, H. J., M. Gwen, J. Kujawski, N. Melvin, J. Englert, C. Miller, et al. Mid Atlantic Region Grass Collections Efforts at the University of Maryland in Support of the NRS-PMCs. In *Proceedings of the Second Eastern Native Grass Symposium*. Baltimore, Maryland, Nov. 17–19, 1999, pp. 318–321.
97. Keyser, P., C. Harper, G. Bates, J. Waller, and E. Doxon. *Establishing Native Warm-season Grasses for Livestock Forage in the Mid-South*. SP731-B. Tennessee State University Cooperative Extension Program, 2011.
98. Texas Department of Transportation (TxDOT). *Roadside Vegetation Management Manual*. Austin, Texas, 2009.
99. West, T., and E. Marshall. Managing Sown Field Margin Strips on Contrasted Soil Types in Three Environmentally Sensitive Areas. *Aspects of Applied Biology*, Vol. 44, 1996, pp. 269–276.
100. De Cauwer, B., D. Reheul, K. D'hooghe, I. Nijs, and A. Milbau. Evolution of the Vegetation of Mown Field Margins Over Their First 3 Years. *Agriculture, Ecosystems and Environment*, Vol. 109, No. 1, 2005, pp. 87–96.
101. Hallet R. INDOT has a Blooming Program. In *Indiana Economic Digest*. Montgomery County, Indiana, Sept. 18, 2008.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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