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THE EFFECTS OF REDUCED MOWING IN ROADSIDE
MEDIANS ON STORMWATER FILTRATION AND
INVASIVE SPECIES MANAGEMENT

BY

SARA WIGGINTON

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN BIOLOGICAL AND ENVIRONMENTAL SCIENCES
IN
ECOLOGY AND ENVIRONMENTAL SCIENCES

UNIVERSITY OF RHODE ISLAND

2015

MASTER OF SCIENCE IN BIOLOGICAL AND ENVIRONMENTAL SCIENCES
OF
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2015

ABSTRACT

Roadside ecosystems are the pervasive, highly managed areas adjacent to roads that buffer neighboring ecosystems. While frequently studied and managed at significant cost to ensure motorist safety, roadside ecosystems are often undervalued for their ecological functions (e.g., water filtration, carbon storage, wildlife habitat). Reducing roadside mowing can provide native habitat, save money, and reduce habitat fragmentation. However, transitioning to a reduced mowing maintenance regimen raises concerns that invasive plants may proliferate. On roadside ecosystems with different mowing regimens, we tested the hotly debated diversity-stability hypothesis, which posits that high native species diversity may confer resistance to invasion. To test this relationship, we surveyed vegetation at four spatial scales (1000-m², 100-m², 10-m², and 1-m²) using Modified-Whittaker plots in three types of roadside ecosystems—forested, early successional, and frequently mowed grasslands— under three types of vegetation management— Never Mowed (N=5), Reduce Mowed (N=5), and Fully Mowed (N=5). We then compared total, native, introduced (any non-native flora), and invasive (plants with a state conservation status of invasive) plant diversity and percent plant cover. We found that roadside ecosystems with high native plant species diversity tended to have the lowest introduced species richness at all four spatial scales. This evidence supports the diversity-stability hypothesis in these highly disturbed and human-manipulated areas. We also found that Never Mowed sites had higher species richness than Fully Mowed sites ($P=0.046$), higher native species richness than Fully and Reduce Mowed sites at the two largest spatial scales (1000-m² $P=0.0001$, 100-m² $P<0.0001$), lower introduced species richness than Fully and

Reduced Mowed sites at three spatial scales (100-m² $P=0.003$, 10-m² $P=0.003$, 1-m² $P<0.0001$), and less introduced species percent cover ($P=0.0001$) when compared to adjacent communities. We found no significant differences between the community composition of Fully Mowed and Reduce Mowed communities. Additionally, we did not observe differences in invasive species richness or percent cover by mowing regimen. In addition to invasive species monitoring, we performed stormwater filtration monitoring to insure that this vital ecosystem provided by roadside ecosystems was not negatively affected by this change in maintenance. To determine if changes mowing practices affect filtration of pollutants, we analyzed soil water concentrations of Al, Cd, Cu, Fe, P, Pb, Mg, Mn, Ni, Zn, NO₃, and NH₄ in Frequently mowed (N=5) and Reduce mowed (N=5) roadside communities in Rhode Island using buried Ion-exchange resin membranes. We found that only iron (Fe) was significantly lower in concentration ($p=0.04$) than other nutrients and metals in Reduce mowed communities suggesting that reducing mowing on roadsides will not reduce the filtration services in a meaningful way. Based on these results, we recommend reducing or ceasing to mow roadsides where safety allows as it facilitates native biodiversity, is a cost-saving approach to passive restoration, and maintains early successional habitat, important for supporting rare and endangered wildlife.

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PREFACE

This thesis is prepared in Manuscript format containing two papers.

In 2010, The Rhode Island Department of Transportation (RIDOT) began a reduced roadside mowing maintenance regimen to conserve funds and decrease CO₂ emissions. To better understand the effects of altering roadside mowing regimens, I developed an experimental design to capture the effects of this reduced mowing on roadsides in different zones and in sites throughout the state. The first chapter discusses invasive plant colonization in areas where mowing has been reduced or eliminated because it is often assumed that reducing mowing will lead to an increase in invasive plant colonization. Because roads are highly disturbed and because they can act as invasion corridors, it is vital to better understand the relationship between mowing regimens and invasive plant colonization. Our data indicate that mowing treatment does not affect invasive species colonization and that roadside areas that are not mowed have the highest native plant biodiversity. In the first chapter, I also consider how our findings relate to the paradox surrounding the diversity-stability hypothesis. I found that roadsides that fostered higher native richness tended to have lower introduced species diversity and, using a modified Whittaker design, I observed this pattern at four spatial scales.

The second chapter is concerned with monitoring stormwater filtration in areas where mowing has been reduced or eliminated to see if this ecosystem service was affected by this change in management. Roadsides often serve as buffer zones between developed areas and sensitive areas, such as wetlands and croplands. Vegetation in roadsides provides the vital ecosystem service of removing pollutants from runoff

before it enters the surrounding environment through phytoremediation. I compared concentrations of ten nutrient and metal contaminants in frequently mowed and reduced mowed roadsides and found that the difference in vegetation management only effected concentrations of iron.

While this change in roadside vegetation management did not affect the concentrations of the majority of the contaminants I monitored, there are still several advantages of a reduction in roadside mowing. The change in vegetation structure has the potential to slow the flow of runoff, increasing absorption in roadsides and resulting in less runoff entering surrounding wetlands and croplands.

I suggest that moving from frequently mowing roadsides to either very infrequently or eliminating mowing has the potential to reduce management costs, facilitate native biodiversity, and reduce CO₂ emissions. Additionally, a reduction in roadside mowing provides passive restoration opportunities through maintenance of early successional habitat which is important for supporting rare and endangered wildlife. Studies such as this, which seeks to balance human development with ecological function, are of ever growing importance as natural areas become ever increasingly degraded in quality and quantity.

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Manuscript 1-

Submitted for review to PLoS One

Evolving highways: fostering native habitat and conserving funds through passive roadside restoration

Running Title: Evolving Highways

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ABSTRACT

1. Roadside ecosystems are the pervasive, highly managed areas adjacent to roads that buffer neighboring ecosystems. While frequently studied and managed at significant cost to ensure motorist safety, roadside ecosystems are often undervalued for their ecological functions (e.g., water filtration, carbon storage, wildlife habitat). Reducing roadside mowing can potentially increase ecosystem functions, provide native habitat, save money, and reduce habitat fragmentation. However, transitioning to a reduced mowing maintenance regimen raises concerns that invasive plants may proliferate. On roadside ecosystems with different mowing regimens, we tested the hotly debated diversity-stability hypothesis, which posits that high native species diversity may confer resistance to invasion.

2. To test this relationship, we surveyed vegetation at four spatial scales (1000-m², 100-m², 10-m², and 1-m²) using Modified-Whittaker plots in three types of roadside ecosystems—forested, early successional, and frequently mowed grasslands— under three types of vegetation management— Never Mowed (N=5), Reduce Mowed (N=5), and Fully Mowed (N=5). We then compared total, native, introduced (any non-native flora), and invasive (plants with a state conservation status of invasive) plant diversity and percent plant cover.

3. We found roadside ecosystems with a high native plant species diversity tended to have the lowest introduced species richness at all four spatial scales. This evidence supports the diversity-stability hypothesis in these highly disturbed and human-manipulated areas.

4. We also found Never Mowed sites had higher species richness than Fully Mowed sites ($P=0.046$), higher native species richness than Fully and Reduce Mowed sites at the two largest spatial scales (1000-m^2 $P=0.0001$, 100-m^2 $P<0.0001$), lower introduced species richness than Fully and Reduced Mowed sites at three spatial scales (100-m^2 $P=0.003$, 10-m^2 $P=0.003$, 1-m^2 $P<0.0001$), and less introduced species percent cover ($P=0.0001$) when compared to adjacent communities. We found no significant differences between the community composition of Fully Mowed and Reduce Mowed communities.

5. Additionally, we did not observe differences in invasive species richness or percent cover by mowing regimen.

6. We recommend reducing or ceasing to mow roadsides where safety allows as it facilitates native biodiversity, is a cost-saving approach to passive restoration, and maintains early successional habitat, important for supporting rare and endangered wildlife.

Keywords: biotic-resistance, diversity-stability, DOT, FHWA, fragmentation, habitat restoration, management, passive restoration

Introduction

In the United States alone, there are over 100,000 square kilometers of public road surfaces and associated roadside ecosystems (Forman 2004), an area greater than the country of Iceland. Roadside ecosystems, the managed areas adjacent to roads that buffer neighboring ecosystems, represent 45% of this total (Forman 2004), approximately the area of Massachusetts and Vermont combined (U.S. Census Bureau 2010). Because of their ubiquity, roadside ecosystems provide an important conservation opportunity, but many are undermanaged, underutilized, and undervalued for their ecological functions. Roadside ecosystems can provide refugia for rare native plants (Forman et al. 2003, Forman and McDonald 2007, Brown and Sawyer 2012) and create buffer zones between urban areas and sensitive ecosystems like wetlands by filtering pollutants from storm water runoff (Rammohan 2006). However, roads and roadway activities are also a major cause of landscape fragmentation, habitat loss, and non-point source pollutants (US EPA 1990, Laurance 2014). As natural landscapes continue to decrease, changing management of the vast global roadside ecosystems may provide opportunities to mitigate the negative effects of highly engineered areas, particularly in regions where there is high road density and narrower roadside buffer zones relative to other regions (Forman 2003). These highly disturbed areas are also vulnerable to plant invasions (Forman and McDonald 2007), but maintenance of high native species diversity may confer resistance to invasion (Elton 1958, Tilman 1999).

Vegetation establishment and control, including mechanical control through mowing, is a major tool of roadside management. Frequent mowing can improve driver safety by increasing sight lines, reducing fire fuel loads, and decreasing costs associated with

control of some invasive plant species (AASHTO 2011). However, mowing is an unnatural, frequent, and intense disturbance, is expensive in terms of labor and fuel, can facilitate the spread of invasive plants, and can result in up to ~22 kilogram of CO₂ emissions per shoulder-mile (AASHTO 2011, Sonntag et al. 2011, Cal-IPC 2012). The timing of mowing is also an important consideration; mowing invasive annuals while in flower before seeds set can prevent seed spread and successfully control annual plant invaders resulting in an advantage for perennial species (DiTomaso 2000). Additionally, mowing roadsides into the autumn can decrease protective cover for wildlife species that would otherwise use these habitats during winter months (Harper 2007).

To balance the pros and cons of mowing, many state Departments of Transportation (DOTs) have altered vegetation control guidelines to reduce mowing in areas where driver safety is not affected (AASHTO 2011). A reduction in mowing frequency may reduce CO₂ emissions, habitat fragmentation, and management costs, and create more suitable habitat for some wildlife (AASHTO 2011). Roadside habitat undergoing reduced mowing treatments transitions from frequently mowed grasslands to early successional wildlife habitat. McCleery et al. (2015) found that many avian species increase use of roadside habitats when vegetation is taller and thicker. This change in habitat structure could also help species at risk, such as the New England cottontail (*Sylvilagus transitionalis*), that suffer from decreased availability of early successional habitat in New England. Fenderson et al. (2014) found that although major highways can be barriers to New England cottontail dispersal, the adjacent habitat can actually facilitate connectivity between populations. In Denmark, skylarks (*Alauda arvensis*) were observed to prefer roadsides for foraging and nesting over areas adjacent to roadsides

(Laursen 1981) and ruffed grouse (*Bonasa umbellus*) seem to prefer roadside habitat to developed areas and coniferous forests (Endrulat et al. 2005). Meadow butterflies, such as the ringlet (*Aphantopus hyperantus*), bees, and other pollinating species have also been shown to utilize restored roadside habitat (Ries et al. 2001, Hopwood 2008). Valtonen and Saarinen (2005) observed ringlet butterflies in several types of roadsides and found that this species occurs at higher densities in areas that are either not mowed or mowed in the late summer, compared to those that are mowed in the early summer.

A major concern of transitioning to reduced mowing on roadsides is increasing weedy and invasive plant species establishment and spread. Many invasive plants are fast-growing, shade intolerant, and disturbance tolerant - traits that allow them to thrive in roadsides (Harper-Lore and Wilson 2000, Forman and McDonald 2007). In addition to providing good habitat for invaders, roadsides provide a pathway for facilitated dispersal. Vehicles, wildlife, and wind move propagules along the roadside, increasing the range of non-native and invasive plants (Forman and McDonald 2007, Mortensen et al. 2009). Unmanaged invasive roadside plants can crack road surfaces, impede drainage, and damage communication infrastructures (Perron 2008). Once established, significant resources are often necessary for any level of control and eradication may not be possible (Perron 2008). For these reasons, it is vital to monitor roadsides with reduced mowing to limit invasive establishment and to engage in early detection followed by rapid responses when invasive species are detected (Pyšek and Richardson 2010). Additionally, it is key to monitor the richness and abundance of native and introduced species to ensure state agencies are meeting national goals set by the FHWA to encourage growth of native plant species in roadsides (AASHTO 2011).

We quantified the effects of different mowing regimens on roadside plant community composition in Rhode Island which averages one hectare of mowed roadside per kilometer of the state's nearly 22,000 total kilometers of publically managed roads (Brown et al. 2012). State owned roads comprise 22% of this total (Rhode Island Office of Management and Budget 2012), leaving the Rhode Island Department of Transportation (RIDOT) to manage nearly 5,000 hectares of roadside habitat. Following regional trends, Rhode Island implemented a reduced mowing maintenance regimen in a many areas of the state over the last decade, including much of Interstate-295 and sections of Interstate-95 where taller vegetation does not impede horizontal sight distance. This shift has brought about two changes: First, mowing of the clear/operational zone (Figure 1) has been reduced from 4-6 mows to 1-3 mows per year. The clear zone must at a minimum be mowed once annually to prevent the regrowth of woody vegetation and to keep it safe for erratic vehicles to regain control. Second, mowing was eliminated in the transition zone where a full mow was the historic maintenance practice (W. Whalen, RIDOT, personal communication, Figure 2). The elimination of mowing resulted in patches of open grassland - a mixture of native and introduced grasses, mowing-tolerant forbs, and small shrubs (Brown and Sawyer 2012, Appendix S1 in Supporting Information: Figure S1).

We quantified the effects of mowing frequency on native and introduced plant abundance in Rhode Island by surveying roadsides under three different mowing regimens (

Table 1) allowing us to compare roadside communities in different stages of succession for species richness and percent cover. Rhode Island is an appropriate case study for analyzing the effect of passive roadside habitat restoration because—like much of the nation—natural areas are decreasing as development continues to increase, especially in more urban areas (Leddy and Nelson 1999). We predicted that: (1) Never Mowed communities would have the highest native species richness and cover because they are less disturbed; (2) Fully Mowed and Reduce Mowed communities would have a greater percent cover of introduced plants relative to Never Mowed communities because they experience more disturbance; and (3) Reduce Mowed communities would have the highest total species richness, native species richness, and introduced species richness because these communities are under an intermediate amount of disturbance compared to the other two treatments (Connell 1978, Sousa 1979), and they will also have the greatest invasive species richness because they are undergoing natural succession and are at risk for invasive establishment.

Materials and Methods:

Site Selection

Roads were mapped using ArcGIS 10.2 and Rhode Island Geographic Information System (RIGIS) mapping layers. Working closely with roadside managers at RIDOT, we visited 50 possible sites that fell into one of three mowing treatment categories: “Frequently mowed”, “Reduce Mowed”, and “Never Mowed” (

Table 1). Then, using a RIDOT map layer, we analyzed sites for annual average daily traffic (AADT) and all sites that were over 50,000 AADT were excluded for safety reasons. After this, we surveyed sites for characteristics shown to be significant to establishment of roadside vegetation. This includes soil type, soil hydrology, surrounding land use, hydrological condition, general slope, and aspect (Appendix S1: Table S1, Table S2). These factors were kept as constant as possible across sites and site type. The final consideration for site selection was to ensure that sites were selected to evenly represent limited access highways across the state of Rhode Island as much as possible (Appendix S1: Figure S2).

Maintenance:

All roadsides included in this study are located in Rhode Island and are managed by RIDOT. New Holland tractors with double flail mowers were the most commonly used mowers by RIDOT roadside maintenance crews. While rotary mowers may also have been used at some sites, Parr and Way (2014) found that the type of mower used does not affect vegetation community composition.

Vegetation Surveys:

At each site we used a nested plot design to assess plant communities at multiple scales. Specifically, we performed a modified Whittaker vegetation survey (Stohlgren 1995) to collect a comprehensive list of species during peak vegetation (

). The entire plot was 20-m wide and 50-m long (1000-m²), and contained 13 subplots of three different sizes: One 5-m by 20-m (100-m²) subplot (C) was located in the middle of the plot, two 2-m by 5-m (10-m²) subplots (A and B) were at opposite corners of the plot, and ten 0.5-m by 2-m (1-m²) subplots were located around the perimeter of the main and center plots. Six of the 1-m² subplots were placed around the inside of the plot perimeter border, while the other four were placed around the outside perimeter of the center subplot.

All vegetation surveys were performed from July 18-August 15, 2014 during peak vegetation. We recorded all species present in subplot A, B, and C and then surveyed the 10 small subplots recording species, mean height, and estimated percent cover. We then surveyed the rest of the 1000-m² plot and recorded any species that not present in the subplots. Any broad leaf species not identified in the field were collected and later identified using a dichotomous key. Grass species were collected, planted in a greenhouse, allowed to flower and then identified under a compound microscope using Phillips 1962. The 3% of plants that could not be identified to species were identified to genus and considered as individual species when calculating species richness, but were not included in native, introduced, or invasive species richness or percent cover calculations.

Species were categorized as “native,” “introduced,” and/or “invasive” based on classifications by “GoBotany” (gobotany.newenglandwild.org). All species native to Rhode Island were categorized as “native,” all non-native species were categorized as

“introduced” and those introduced species which have a conservation concern of invasive were classified as “invasive.”

Data Analysis:

All data analysis was done in R Studio software and $P < 0.05$ was used to determine significance for all tests. We used one-way Analysis of Variance (ANOVA) to assess differences in community composition of different site types at the 1000-m² and 100-m² spatial scales. For analysis of 10-m² and 1-m² subplots, data was averaged across site and one-way ANOVAs were used. We calculated differences in total species richness, native species richness, introduced species richness, and invasive species richness at all four spatial scales. An ANOVA was also conducted on the Shannon-Weiner and Simpson’s diversity index value for each site to capture richness and evenness measurements. We also compared percent cover of native, introduced, and invasive species at the smallest spatial scale (1-m²) across site type. We used ANOVA to compare subplots in the clear zone by site type. The same was done for subplots not within the clear zones. Tukey HSD tests were used when the ANOVA returned significant differences. Additionally, we used non-parametric Wilcoxon-Mann-Whitney tests to compare richness and cover between the clear zone and the transitional zone.

Results

Species Richness, Native Richness, Introduced Richness, Invasive Richness

At the 1000-m² scale, the only significant difference found in species richness was between Fully Mowed and Never Mowed sites ($F=3.69$, $P=0.046$, Appendix S1: Table S3). The average native species richness at the 1000-m² scale was significantly different between mowing treatments ($F= 21.46$, $P=0.0001$, Appendix S1: Table S3, Figure S3). A post hoc comparison using Tukey HSD test indicated that the mean of Fully Mowed and Reduce Mowed sites were significantly different than the mean of Never Mowed sites ($P=0.0001$, $P=0.002$, Appendix S1: Table S3). This test also indicated that there was not a significant difference between the mean of Fully and Reduce Mowed sites (Appendix S1: Table S3). There were no significant differences in the mean of introduced or invasive species richness between mowing treatments at the largest spatial scale (Appendix S1: Table S3).

At the 100-m² scale, an ANOVA indicated a significant difference in native species richness between mowing treatments ($F=23.12$, $P<0.0001$), Appendix S1: Table S3, Figure S4). A Tukey HSD test showed that there was a significant difference Fully Mowed and Never Mowed ($P<0.0001$), as well as between Reduced Mowed and Never Mowed ($P= 0.002$), but not between Fully Mowed and Reduce Mowed (Appendix S1: Table S3). The means of introduced species richness were significantly different ($F=9.71$, $P=0.003$, Appendix S1: Table S3, Figure S5) between Fully Mowed and Never Mowed ($P=0.003$) and between Reduce Mowed and Never Mowed ($P=0.038$, Appendix S1: Table S3). There was no significant difference between the mean number of introduced species in Fully Mowed and Reduce Mowed sites (Appendix S1: Table S3) or

between average total species richness and invasive species richness between treatment types in the 100-m² subplot (Appendix S1: Table S3).

The average introduced species richness in the 10-m² subplots was significantly different across site type ($F=9.93$, $P=0.003$, Appendix S1: Table S3, Figure S6), specifically between Fully Mowed and Never Mowed sites (Tukey HSD $P=0.005$), as well as between Reduce Mowed and Never Mowed sites ($P=0.008$) but no significant differences were found in introduced species richness between Fully Mowed and Reduce Mowed sites (Appendix S1: Table S3) or in total species richness, native species richness, or invasive species richness (Appendix S1: Table S3).

At the 1-m² scale, the differences in the mean native species richness were significant for treatment ($F=4.69$, $P=0.031$, Appendix S1: Table S3, Figure S7) and a Tukey HSD test indicated this was only between Fully Mowed and Never Mowed sites ($P=0.025$). There was not a significant difference in native species richness between Fully Mowed and Reduce Mowed site or between Reduce Mowed and Never Mowed sites (Appendix S1: Table S3). These means of introduced species richness were found to be significantly different using a one-way ANOVA ($F=22.15$, $P<0.0001$, Appendix S1: Table S3, Figure S8). A Tukey HSD test indicated that the significant differences were between Fully Mowed and Never Mowed ($P=0.0001$) as well as between Reduce Mowed and Never Mowed ($P=0.0005$, Appendix S1: Table S3). There was no significant difference in introduced species richness between Fully Mowed and Never Mowed sites. No significant differences were observed in total species richness or invasive species richness at the smallest spatial scale (Appendix S1: Table S3).

Native Species Cover, Introduced Species Cover, Invasive Species Cover

The mean introduced species percent cover was significantly different between mowing treatments ($F=23.16$, $P<0.0001$, Appendix S1: Table S3, Figure S9). A Tukey HSD post hoc test indicated that the difference between the mean introduced species cover was significant between Fully Mowed and Never Mowed sites ($P=0.0002$), as well as between Reduce Mowed and Never Mowed sites ($P=0.0003$, Appendix S1: Table S3). There were no significant differences in native or invasive species percent cover between any mowing treatments (Appendix S1: Table S3).

Zonal Effects

When only subplots located within the clear zone were considered, only native and introduced percent cover were significantly different between mowing treatments ($F=8.63$, $P=0.005$; $F=5.57$, $P=0.018$; Appendix S1: Table S4). A Tukey HSD test indicated that the difference in native percent cover was between Fully Mowed and Never Mowed ($P=0.027$, Appendix: Table S4) and between Reduce Mowed and Never Mowed ($P=0.005$, Appendix S1: Table S4). The significant difference in introduced percent cover was between Reduce Mowed and Never Mowed sites ($P=0.018$, Appendix S1: Table S4).

When only subplots located within the transition zone were considered, native species richness, introduced species richness, and introduced percent cover were all significantly different between site type ($F=6.94$, $P=0.01$; $F=10.59$, $P=0.002$; $F=15.43$, $P=0.0005$; Appendix S1: Table S4). The differences between native richness were between Fully Mowed and Never Mowed sites ($P=0.008$, Appendix S1: Table S4). The

significant difference for introduced species richness and introduced species percent cover were both between Fully Mowed and Never Mowed sites ($P=0.003$; $P=0.0007$; Appendix S1: Table S4), and between Reduce Mowed and Never Mowed sites ($P=0.008$, $P=0.002$; Appendix S1: Table S4).

When richness, native richness, introduced richness, invasive richness, native percent cover, introduced percent cover, and invasive percent cover were compared between subplots of all spatial scales within the clear zone and in the transitional zone across all site types using a Wilcoxon-Mann-Whitney test, only invasive species richness was found to be significantly different ($P=0.019$, Appendix S1: Table S5). When the two zones were compared for Fully Mowed sites only, native species richness was significantly different ($P=0.022$, Appendix S1: Table S5). Never Mowed sites zones had significantly different introduced species richness ($P<0.0001$, Appendix S1: Table S5), invasive species richness ($P=0.022$, Appendix S1: Table S5), native percent cover ($P=0.025$, Appendix S1: Table S5), and introduced percent cover ($P=0.013$, Appendix S1: Table S5). The same comparisons in Reduce Mowed sites only yielded not significant differences (Appendix S1: Table S5).

Discussion

Disturbance, Invasibility, and Fragmentation

Natural disturbance regimens are vital to the maintenance of many ecosystems and play a part in maximizing species diversity, but can also increase opportunities for plant invasions (Hobbs and Huenneke 1992). Many ecosystems no longer experience historic disturbances such as wildfires or grazing, because of anthropogenic activities, while others experience unnaturally high levels of disturbances, such as eutrophication, soil disturbance, fragmentation, and intense biomass removal. Roadway activities include biomass removal by mowing and fragmentation through road construction, which affects the movement and connectivity of fauna and flora in many ecosystems, increases the amount of edge habitat in the landscape, and the layout of the landscape matrix (Hobbs and Huenneke 1992).

Like many forms of disturbance, mowing has advantages such as increased safety and habitat. While mowing has been observed to promote higher species diversity, excessive mowing can exclude perennial species while promoting the growth of annuals (Schippers and Joenje 2002). Annual species are generally weedier and have less belowground biomass than perennials resulting in reduced storm water filtration, a key service of roadside ecosystems (Rhode Island Office of Management and Budget 2012). Higher native species diversity may confer resistance to invasion, as predicted by the biotic resistance diversity-stability hypothesis (Elton 1958, Case 1990), due to the tightly constructed niche partitions that arise when many species co-occur. Conversely, communities with low diversity are thought to be at a relatively higher risk of invasion because of increased availability of limiting resources. The biotic resistance hypothesis

has been tested and supported by some studies using competition models and small-scale field experiments that found negative relationships between community biodiversity and invasion (Case 1990, Tilman 1999). Alternatively, other studies found that high diversity promotes fluidity and instability in community composition with species regularly entering and exiting systems, opening opportunities for invader establishment, known as “The Rich Get Richer” hypothesis (Stohlgren et al. 2003). This hypothesis has found support among researchers investigating community composition at larger scales where there are documented positive relationships between exotic and native species richness in natural areas (Stohlgren et al. 1999, Stohlgren et al. 2001) as opposed to the heavily human-altered habitats studied here. These opposing patterns at varying scales are known as the “invasion paradox” (Fridley et al. 2007).

In our roadside study, we found that there was an inverse relationship between native species richness and introduced species richness; we found the highest native species richness and the lowest introduced species richness in forested sites, and the lowest native species richness and highest introduced species richness at the most disturbed (through mowing) sites. This pattern supports the diversity-stability hypothesis, with the fewest introduced species established where native biodiversity is the highest. These results are not surprising because of the similarities between roadside ecosystems in Rhode Island and the highly managed plots surveyed in by David Tilman that support the biotic resistance hypothesis (Tilman 1999). Both roadside sites and grassland plots at Cedar Creek Long Term Ecological Research station are removed from natural landscapes, seeded with specific grasses, and managed by mowing—at least on the edges of the plots/sites. The diversity-stability hypothesis has not been supported in areas that are not

as fragmented or as removed from the surrounding landscape matrix as are the plots at Cedar Creek and Rhode Island roadside. For example, Stohlgren et al. (1999) performed Modified-Whittaker surveys at multiple sites in National Parks and Monuments in the Colorado Rockies and at multiple sites in stations in the Central Grasslands. They found that the diversity-invasibility hypothesis was only supported at the subplot and plot spatial scales and only in the Central Grasslands. At all spatial scales in the Colorado Rockies and at the biome level in the Central Grasslands, they found that exotic species diversity was positively correlated with total biodiversity. Additionally, when Stohlgren et al. (2003) analyzed large patterns of diversity and invasibility across the United States, one of the two main data sets they used were collected as part of the USDA Forest Service's Forest Health Monitoring Initiative-- areas also likely to be less fragmented and disturbed than our roadside sites.

Because of the highly fragmented nature of the roadside systems, these roadside and median areas are often separated from the surrounding landscape matrix by four plus lanes of road, creating a network of island-like habitats for those species that are dispersed (purposefully or accidentally) to these areas. This island attribute can make them especially susceptible to establishment by exotic species (Elton 1958, Reaser et al. 2007), edge effects, and decrease vegetation structure heterogeneity (Saunders et al. 1991). Therefore, to minimize the negative effects of fragmentation, roadside patches should be as wide as possible because increasing the core areas will decrease instability in community composition by decreasing localized extinctions (Saunders et al. 1991) which will increase the stability of the native biodiversity. Reconsidering roadsides as important habitat that provide significant ecosystem services, including safety, and

altering management of these systems accordingly, may help to achieve conservation goals for some species, while reducing emissions of CO₂ and other greenhouse gases.

Management Implications

Areas with the highest native biodiversity always contained the lowest introduced biodiversity, supporting the biotic resistance hypothesis. This correlation of high native and low introduced diversity was not affected by spatial scale. However, spatial scale did affect native and introduced richness, but not in the same way. P-values were graphed to show how the strength of the relationship between native/introduced diversity and mowing treatment varied by scale. The relationship between mowing treatment and native biodiversity shows a general increase in strength as scale increases, while the relationship between introduced diversity and treatment generally decreases in strength with an increase in scale (**Error! Reference source not found.**). This trend is strongest when looking at the p-values for the difference in Reduced and Never Mowed communities only (Figure 4). This suggests that there may be different mechanisms driving native and introduced richness and that these mechanisms operate at different spatial scales. Specifically, control efforts of introduced plants should occur at smaller spatial scales while managing for native plants on roadsides should occur at larger scales.

Mowing does not affect invasive plant richness or cover, but increases introduced richness at these sites. Because areas under a reduced mowing regimen are mowed less frequently—mowing—an effective management strategy for many invasive species (AASHTO 2012) — we predicted that these areas would have significantly higher occurrences and density of invasive species than areas managed as forests or as

frequently mowed grasslands. One explanation for our result may be that invasive species have not yet had a chance to colonize these areas and continued monitoring may reveal a different pattern. Introduced species, however, occurred more frequently and in higher densities in areas that are mowed completely and those undergoing early succession. While the majority of the introduced species in Rhode Island roadsides are not considered invasive, it is still important to monitor their abundance and spread because many introduced species may transition into invasiveness, after a lag-time, or when under the right environmental conditions (Reaser et al. 2007). The change in roadside maintenance created a large amount of new early successional habitat, an uncommon ecosystem in New England and elsewhere (Brown and Sawyer 2012), which could eventually facilitate some roadside invaders.

Our results suggest that habitats with the least amount of disturbance have greater native species richness and fewer non-native species due to reduced resource availability. Forested communities are also at a reduced risk of introduced propagule introduction through roadside maintenance practices. When roadside mowing is performed, reproductively viable plant parts of introduced species can be transported to new locations on the blades of improperly cleaned mowers potentially causing their introduction elsewhere. Because mowers only enter the clear zone of forested communities, there is a decreased opportunity for propagules to successfully establish within the transition zone. Indeed, we saw a significantly higher occurrence and percent cover of both introduced and invasive species in the clear zones adjacent to forested areas than within the forests themselves. Additionally, the narrow clear zones adjacent to forested communities had a significantly higher cover of native species and lower cover

of introduced species compared to communities managed as frequently mowed grasslands. A potential explanation for this is that mowed areas next to forested communities are under higher propagule pressure from native species, which are at higher densities in forests and under lower propagule pressure from introduced species, which are at lower densities in forests.

When we analyzed only those subplots—eight of the ten 1-m² plots, one 10-m² subplot, and the 100-m² subplot— in the transition zone (Figure 1), we observed all of the same significant differences as when both zones were included. As for native species richness, we predicted that significance would increase when only the transition zone was considered since this is where different management was occurring. However, the relationships between site type and community composition decreased in strength when only the transitional zone subplots were considered for introduced species richness and cover. Because of these observations, it is obvious that the clear zone is highly influenced by the adjacent ecosystem in the transition zone; the community structure of the transitional zone may be more important than the maintenance practice the clear zone is receiving.

Reduced mowing on roadside ecosystems does not create plant communities that significantly differ in native and invasive plant species diversity from those roadsides managed through frequent mowing. This suggests that changing mowing maintenance practices may be less important for invasive plant control than previously assumed and that reducing mowing can have benefits of decreasing management costs to state and federal agencies while also reducing CO₂ emissions. However, because the practice of reduced mowing has been in place for <10 years in our study area, continued monitoring

is needed to determine whether invasive and introduced species will eventually increase significantly above those frequently mowed communities.

Based on this study, communities that are not mown may be most beneficial to ecosystems adjacent to roadside habitats because they contain the highest native species diversity and the lowest introduced species diversity. However, native vs. introduced richness is not the only consideration. Because we did not see significantly higher invasive species richness or cover in areas undergoing a reduction in mowing, these early successional habitats may be desired over forested communities because of their potential as important early successional habitat for species that require it. Keeping roadside ecosystems in early succession would require carefully timed and considered maintenance, but could add a great deal of beauty and ecological function to landscapes through passive restoration, while saving money and reducing greenhouse gas emissions.

Table 1: Vegetation Community Type Descriptions

Community:	Description:
Frequently Mowed	Mowed completely 3-6 times a year- Medians are mowed pavement to pavement; shoulders are mowed far past clear zone. Dominated by short grasses, such as crab grass.
Reduce Mowed	Only the clear zone is mowed; areas have not been mowed for 3-10 years. Is characterized by tall grass, shrubs, and small trees. Early successional.
Never Mowed	Area that has not been historically maintained through mowing, characterized by self-sustaining communities dominated by trees. “Young” forest.

Figure Legends:

Figure 1- Highway Zonal System. Zone 1: Vegetation free zone, Zone 2: Operational/Clear Zone, Zone 3: Transition Zone. (Recreated from FHWA 2009).

Figure 2- Example of an area under a reduced mowing maintenance regimen. Mowing eliminated in the transition zone and reduced in frequency in the clear zone.

- Modified Whittaker plot diagram, source National Institute of Invasive Species Science, Colorado State University, Fort Collins, CO. (www.NIISS.org)

Error! Reference source not found.- P-values of ANOVAs run on the native and introduced species richness of all three community types.

Figure 4- P-values of ANOVAs run on the native and introduced species richness in reduced versus Never Mowed communities, calculated by Tukey's HSD.

Figure

Figure 1- Highway Zonal System. Zone 1: Vegetation free zone, Zone 2: Operational/Clear Zone, Zone 3: Transition Zone. (Recreated from FHWA 2009).

Figure 2-- Example of an area under a reduced mowing maintenance regimen. Mowing eliminated in the transition zone and reduced in frequency in the clear zone.

Figure 3- Modified Whittaker plot diagram, source National Institute of Invasive Species Science, Colorado State University, Fort Collins, CO. (www.NIISS.org)

Figure 4- P-values of ANOVAs run on the native and introduced species richness of all three community types.

Figure 4- P-values of ANOVAs run on the native and introduced species richness in reduced versus Never Mowed communities, calculated by Tukey's HSD.

Supporting Information:

Additional supporting information may be found in the appendices of this thesis.

Appendix S1: Additional Methods and Analysis Details

Figure S1: Comparison of Fully Mowed and Reduce Mowed roadsides in Rhode Island.

Table S1: Road Characteristic related to invasive plant establishment

Figure S2: Map of Roadside Sites in Rhode Island.

Figure S3: Box plot representing the difference of native species richness between mowing treatments at the 1000m² spatial scale.

Figure S4: Box plot representing the difference of native species richness between mowing treatments at the 100m² spatial scale.

Figure S5: Box plot representing the difference of introduced species richness between mowing treatments at the 100m² spatial scale.

Figure S6: Box plot representing the difference of introduced species richness between mowing treatments at the 10m² spatial scale.

Figure S7: Box plot representing the difference of native species richness between mowing treatments at the 1m² spatial scale.

Figure S8: Box plot representing the difference of introduced species richness between mowing treatments at the 1m² spatial scale.

Figure S9: Box plot representing the difference of introduced species richness between mowing treatments at the 1m² spatial scale.

Table S2: Site details.

Table S3: Results of one-way ANOVAs comparing total species richness, native species richness, introduced species richness, and invasive richness between Site Types

Table S5: Results of non-parametric Wilcoxon-Mann-Whitney between all subplots within the clear zone to all the subplots in the transitional zone.

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Managing roadsides to maximize ecosystem services

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Abstract

Roadways intersect nearly every ecosystem in the U.S. and their construction can significantly decrease the natural ecosystem services provided by the habitats they replace. The adjacent roadside ecosystem, however, can provide important ecosystem services including filtration of storm water pollutants from road runoff. In the last decade, the Federal Highway Association and U.S. Department of Transportation have encouraged state transportation agencies to reduce mowing in roadside ecosystems as a way to reduce costs, lower CO₂ emissions, and increase storm water filtration. However, few studies have explored whether altering roadside mowing practices have a negative impact on ecosystem services provided by resident plant communities. To determine if changes mowing practices affect filtration of pollutants, we analyzed soil water concentrations of Al, Cd, Cu, Fe, P, Pb, Mg, Mn, Ni, Zn, NO₃, and NH₄ in Frequently mowed (N=5) and Reduce mowed (N=5) roadside communities in Rhode Island using buried Ion-exchange resin membranes. We found that only Fe was significantly lower in concentration ($p=0.04$) than other nutrients and metals in Reduce mowed communities suggesting that reducing mowing on roadsides will not reduce the filtration services in a meaningful way but will provide important benefits such as reducing CO₂ emissions and lowering maintenance costs.

Keywords: storm water, phytoremediation, runoff, FHWA, DOT, filtration

Introduction

There are an estimated 6.3 million kilometers of public roads in the United States (Forman *et al.* 2003). The adjacent roadside ecosystems—managed right-of-ways and medians— occupy an area of 50,000 square kilometer (Forman 2004). This area of public roads and road corridors is roughly the size of the state of Kentucky and contains an ever-increasing percentage of the remaining semi-natural landscape (Forman *et al.* 2003, Forman 2004). Roadsides are primarily managed to facilitate motorist safety but can also be managed to maximize ecosystem services. Roadsides provide habitat for native and state-listed species (Brown and Sawyer 2012, Wigginton and Meyerson in review), serve as crucial buffer zones between developed land and the natural environment, and can filter storm water runoff before it enters sensitive ecosystems such as wetlands (Brown and Sawyer 2012, Forman *et al.* 2003). Storm water runoff pollutants include heavy metals, nutrients, road salt, and suspended solids (Rammohan 2006) that can have toxic effects on aquatic organisms and cause eutrophication (Forman *et al.* 2003). Because roadsides provide these valuable services, state and federal transportation agencies must employ management practices to insure that roadsides continue to filter as many pollutants from storm water as possible to protect surrounding waterways and other sensitive ecosystems. Achieving this while implementing changes in management practices that do not jeopardize motorist safety or increase the spread of invasive species presents a critical challenge.

Highway storm water runoff is a recognized but unquantified source of nonpoint source pollution that is usually grouped with the impacts of other urban and suburban runoff sources (Wu *et al.* 1998). Heavy metals (e.g., Al, Cd, Cu, Fe, Pb, Ni, Zn) and other

harmful pollutants result from many roadway activities including gasoline and exhaust emissions, lubrication oils, grease, and wear on tires, bearings, brake linings, moving engine parts, and paving (Forman *et al.* 2003, Rammohan 2006). Many trace metals pose both short and long-term concerns because they are toxic and persistent, and many accumulate in soils over time without degrading (Sansalone *et al.* 1996). Impairments from highway runoff can cause water bodies to be unsafe for recreational use, may harm aquatic wildlife populations, and can threaten drinking water supplies (EPA 2003). The most recent National Water Quality Inventory found that Urban Runoff/Storm water is among the top ten sources of impairments to the nation's rivers, streams, lakes, estuaries, and bays (EPA 2009).

Carefully managed roadside vegetation can increase filtration of storm water runoff leaving impervious surfaces which significantly improves the quality of water entering waterways (Davis *et al.* 2003). Vegetation can aid in the removal of pollutants (N, P, and heavy metals) from storm water, mine wastewater, and sewage in areas of concern (Read *et al.* 2008) through phytoremediation techniques that utilize plants for their ability to absorb, sequester, and/or degrade contaminants (Cunningham and Ow 1996). In fact, this technique is used to restore soils in degraded ecosystems (Hong 2003) and to manage excess nutrients and metals through constructed wetlands (Carvalho *et al.* 2014). Some plants, such as ferns (Chen *et al.* 2013) are metal hyperaccumulators and are able to uptake metal contaminants from the soil and store them in shoots and leaves (Cunningham and Ow 1996) which can be harvested and disposed of safely. Similar to these approaches, roadside and median vegetated areas can be managed to substantially reduce contaminant loads by decreasing the pollutant concentrations and reducing the

volume of storm water discharged to surface waters (Barrett *et al.* 2006). Nagase and Dunnett (2012) found that the capacity of storm water filtration varies with vegetation structure; short, thin vegetation composition sheds the highest volume of runoff while taller, thicker plants stop and retain the greatest amount of water. A more robust vegetation structure increases rain absorption and soil moisture evaporation due to more extensive root systems while physically slowing the flow of runoff (Nagase and Dunnett 2012).

In order to increase storm water filtration and runoff capture while reducing costs and reducing CO₂ emissions, the Rhode Island Department of Transportation (RIDOT) initiated a reduced mowing maintenance regimen in 2010 in areas of the state where safety would not be compromised (RIDOT 2014). In regions where mowing has been reduced, clear zones (Figure 1) are being mowed less frequently (a shift from 4-6 mows a year to 1-2 annual mows) while medians and shoulders are no longer being mowed at all (Figure 2). The clear zone must be mowed a minimum of once annually to prevent the regrowth of woody vegetation to keep it safe and available for erratic vehicles to regain control (W. Whalen, RIDOT, personal communication, Figure 1). This elimination of mowing has resulted in patches of early successional habitat consisting of native and introduced grasses, small shrubs, and mowing tolerant forbs (Brown and Sawyer 2012, S. Wigginton unpublished data.)

To determine if pollutant removal is affected by mowing practices and vegetation composition, we analyzed pollutant concentrations in two different types of roadside ecosystems throughout Rhode Island: Frequently mowed and Reduce mowed (See Wigginton and Meyerson, in review, for full description of communities). We predicted

that Reduce mowed roadside communities would have a greater capacity for filtering pollutants from highway storm water runoff than Frequently Mowed communities. We also predicted that pollutant concentration would decrease with increased distance from the pavement at all sites, with a more pronounced difference at Reduce mowed sites.

Methods

Site Selection

Roads were mapped using ArcGIS 10.2 and Rhode Island Geographic Information System (RIGIS) mapping layers. Working closely with roadside managers at RIDOT, we visited 50 possible sites. Then, using a RIDOT map layer, we analyzed sites for annual average daily traffic (AADT), and all sites that were over 50,000 AADT were excluded for safety reasons and because it has been shown to have a significant effect on pollutant concentrations (Forman *et al.* 2003). After this, we surveyed sites for characteristics shown to be significant to roadside storm water quality. This includes soil type, soil hydrology, surrounding land use, hydrological condition, general slope, and aspect. These factors were kept as constant as possible across sites and site type. The final consideration for site selection was to ensure that sites were selected to evenly represent limited access highways across the state of Rhode Island as much as possible. Five “Reduce Mowed” and five “Frequently Mowed” sites were selected.

Experimental Design

To analyze storm water runoff for various metal and nutrients, we used ion-exchange resin capsules (IEMs; Dobermann *et al.* 1994, Qian and Schoenau 2002). Resin capsules are small (~2cm, 10 g) mesh balls containing resin beads that serve as a sink for ions in the soil in a similar way as plant roots. These capsules contain thousands of hydrogen (H^+) and hydroxide (OH^-) charged beads that exchange cations and anions in the soils; this allows for an estimation of the plant-available nutrients in the soil (Yang 1991).

We measured two 40-m transects: the first was five meters from the edge of the pavement and the second was 15-m from the edge of the pavement. Using a soil increment core, we installed IEMs in the root zone at a depth of 7.5-cm every 10-m on each transect (Figure 3). The capsules were collected and replaced every 30 days from July-October 2015 giving us four time replications and allowing us to observe pollutant concentration changes over time.

After retrieval, IEMs were transported to the lab in sealed containers on ice where they were immediately rinsed with DI water and refrigerated until extraction. Capsules were leached using a leaching tray (UNIBEST Inc.) with 2 M hydrochloric acid. We then analyzed the leachate for Al, Cd, Cu, Mg, Mn, Ni, P, Pb, and Zn concentrations using an Inductively Coupled Atomic Optical Emission Spectrometry (ICP-AES). To establish the concentration of NH_4 and NO_3 , we performed nutrient assays using a microplate reader (Weatherburn 1967, Doane & Horwarth 2003).

Data Analysis

All data analysis was done in R Studio software and $P < 0.05$ was used to determine significance for all tests. To determine any significant differences in pollutant concentrations between mowing treatments, time replications, distance from pavement, and sites we used one-way Analysis of Variance (ANOVA). Factorial ANOVAs were used to analyze for interaction effects between independent factors. Tukey HSD tests were used when the ANOVA returned significant differences.

Results

Time, Distance, Site, and Treatment effects:

We found that concentrations of Cd, Cu, Fe, Ni, and Pb varied significantly over the four time replications. Cadmium was higher in August than in either July ($p<0.0003$) or September ($p<0.0001$; Figure 4). Copper was significantly higher in October than in August ($p<0.008$) or September ($p<0.0001$; Figure 4); Cu concentrations were also higher in July than in September ($p<0.0001$ Figure 4). Nickel and Iron concentrations were higher in July than in any other month ($p<0.0001$; Figures 4 & 5). Lead concentrations were significantly higher during October when compared to September concentrations ($p<0.04$; Figure 4). Nitrate is lower in July than during any other time replication ($p<0.0001$; Figure 6).

The location of the IEMs in relation to the edge of the pavement also showed significant effects on concentrations of some pollutants. Concentrations of Al ($p=0.008$, Appendix B, Figure S1), Mn ($p=0.02$, Appendix B, Figure S2), and Zn ($p=0.006$, Appendix B, Figure S3) were all significantly higher at 15-m than at 5-m from the edge of the pavement.

There was a significant site effect for Cd ($p=0.006$), with site 12 having significantly lower levels than site one or site five.

There was significantly more Iron at Frequently Mowed Sites than at Reduce Mowed sites ($P=0.04$, Appendix B, Figure S4).

Interacting variable effects:

When we ran a factorial ANOVA on Time period (month) and Site, we found a significant interaction in concentrations of Cd ($p<0.0001$), Cu ($p=0.0007$), and NO_3

($p=0.02$). Additionally, we ran post hoc tests to determine specific significant differences for Time period-Site interaction (Appendix B: Table S1). We also found a significant interaction between Distance and Treatment ($p<0.05$), as well as between Distance and Site ($p<0.0001$), for A1. Ranges and means for all pollutants are presented in Appendix B: Table S2.

Discussion and Conclusions:

Mowing practices did not affect concentrations of any pollutants in Rhode Island roadsides except for iron, which was significantly lower at Reduce mowed sites. This could be because plants are experiencing an iron deficiency since plant available Fe in the rhizosphere is low (Morrissey and Guerinot 2010). Most grass species utilize a chelation-based strategy for acquiring and absorbing iron that involves the release of phytosiderophores that makes iron soluble (Hell and Stephan 2003). This strategy is less affected by soil pH than the alternative strategy for iron sequestration, which is performed by most non-grass species and involves lowering soil pH through release of protons (Hell and Stephan 2003). Because of this, graminaceous species are more efficient at absorbing iron and often survive better in areas of extreme Fe deficiency (Yin and Yuan 2012). However, grasses with a poor root system-- which can result from improper mowing practices-- are not able to take up iron as effectively as plants with more robust roots (Wehner 1992). Because excessive mowing can negatively impact plant roots, and encourage annuals (Schippers and Joenje 2002) which have a less robust root system than perennials, it is not surprising that grasses in Reduce mowed sites are absorbing more iron. Additionally, increased size and structure of vegetation resulting from a reduction in mowing may promote more infiltration of water (Nagase and Dunnett 2012), which in turn may allow for more infiltration of Fe available to plant roots.

An additional, and perhaps more parsimonious, explanation for higher concentrations of Fe at Mowed sites, is the RIDOT cuts vegetation biomass, but performs more removal. Because the mowed clippings remain on the roadsides the nutrients they contain (including Iron) will be recycled and return to the soil during decomposition.

We found a significant increase in concentrations of Al, Mn, and Zn with increased distance from pavement. Al and Zn were both only significant when Frequently mowed sites were included in the analysis. In other words, there were no significant differences in concentrations of these pollutants with respect to the distance from pavement in Reduce mowed areas. This is likely because of the increased aboveground biomass in Reduce mowed communities which has the benefit of slowing down water leaving roadside pavement, potentially increasing opportunities for nutrient and metal uptake and increased filtration via soil. The higher concentrations further from the edge of the road at mowed sites for these three pollutants may also be because particles could be flying for the roads edge over the first line of IEMs.

Average concentrations of many of the pollutants were correlated with average monthly rainfall (Figure 7) because pollutants flush off of roadways and vehicles into roadsides during storm events (Kayhanian *et al.* 2007). As storm frequency and severity increase in much of the contiguous United States with global environmental change (Pryor *et al.* 2009), managers may have to increase mitigation efforts to ensure an increased concentration of roadside pollutants do not enter sensitive ecosystems, such as wetlands, adjacent to roadsides. Pollutants also peaked after larger rainfall events (Figure 8).

One solution would be to install bioswales, storm water basins, and other bioretention areas in regions that will be affected by an increased amount of rainfall and roadsides that are directly adjacent to sensitive ecosystem such as wetlands or croplands. These vegetative control measures have been shown to decrease both the amount of pollutants and runoff entering adjacent ecosystems (Barrett *et al.* 1998). Installing

bioretention systems along roadsides while simultaneously increasing biomass and vegetation structure on roadsides through reductions in mowing will help to ensure that ecosystem services provided by roadsides are maximized, including protecting adjacent agricultural areas from heavy metal contamination.

We did not see significantly lower pollutant filtration in roadsides undergoing reductions in mowing. These findings, in concert with our results that reduced mowing does not increase invasive species establishment and colonization (Wigginton and Meyerson in review), supports the prediction that roadsides can provide the same or potentially more natural ecosystem services under a reduced mowing maintenance regimen. Increasing development and ecosystem disturbance means humans are rapidly degrading many ecosystem services (Millennium Ecosystem Assessment 2005). Therefore, it is critical to ensure that semi-natural managed areas such as road and roadside ecosystems provide and maximize as many ecosystem services as possible. Reduced mowing will conserve highway management funds, decrease CO₂ emissions, foster native wildlife habitat, and increase filtration of storm water before it enters surrounding ecosystems.

Figure Legend:

Figure 1. Clear zone illustration. Source: U.S. Department of Transportation, Federal Highway Association 2009

Figure 2. Example of an area under a reduced mowing maintenance regimen. Mowing eliminated in the transition zone and reduced in frequency in the clear zone

Figure 3. Ion-exchange membrane roadside installation diagram

Figure 4. Changes in concentration of Pb, Cd, Cu, and Ni over time from July 2014-October 2014

Figure 5. Changes in concentration of Fe over time from July 2014-October 2014

Figure 6. Changes in concentration of NO₃ over time from July 2014-October 2014

Figure 7. Average rainfall in study area from July 2014-October 2014

Figure 8- All rainfall events recorded at the Kingston weather station from June 2014-October 2014

Figure 1: Clear zone illustration. Source: U.S. Department of Transportation, Federal Highway Association 2009.

Figure 2: Example of an area under a reduced mowing maintenance regime. Mowing eliminated in the transition zone and reduced in frequency in the clear zone (Wigginton and Meyerson under review).

Figure 3: Ion-exchange membrane roadside installation diagram.

Figure 4: Changes in concentration of Pb, Cd, Cu, and Ni over time from July 2014-October 2014.

Figure 5: Changes in concentration of Fe over time from July 2014-October 2014.

Figure 6: Changes in concentration of NO₃ over time from July 2014-October 2014.

Figure 7: Average rainfall in study area from July 2014-October 2014.

Figure 8: All rainfall events recorded at the Kingston weather station from June 2014-October 2014

Supporting Information:

Additional supporting information may be found in the appendices of this thesis.

Appendix B: Additional analysis details

Table S1: Results of Tukey's HSD post hoc for time period and site factorial ANOVAs for Cd, Cu, and NO₃.

Figure S1: Boxplot representing the difference in aluminum (Al) concentrations accumulated by ion-exchange resin membranes at the two distances from the roadside pavement.

Figure S2: Boxplot representing the difference in Manganese (Mn) concentrations accumulated by ion-exchange resin membranes at the two distances from the roadside pavement.

Figure S3: Boxplot representing the difference in Zinc (Zn) concentrations accumulated by ion-exchange resin membranes at the two distances from the roadside pavement.

Figure S4: Boxplot representing the difference in Iron (Fe) concentrations accumulated by ion-exchange resin membranes in roadsides under two different mowing treatments.

Table S2: Ranges and means for all pollutants

EPILOGUE

I found that a reduced mowing regimen did not cause a significant increase in invasive plant establishment or a decrease in stormwater contaminant filtration. These results suggest that a reduction in roadside mowing is a viable and ecologically sound management change for the Rhode Island Department of Transportation (RIDOT). I believe that RIDOT should begin a reduced mowing maintenance regimen in as many areas of the state as safety allows.

In addition to fostering native habitat and potentially benefiting water quality, reduce mowing has the advantage of being a low-cost passive habitat restoration technique. Many roadside remediations, such as installing bioretention areas, come at a high cost in term of labor, funds, and departmental time. Reduced mowing, however, can increase ecological function of roadsides while saving governmental funds. The ecological benefits for native biota and wildlife have been are well discussed in the first chapter. The potential increase in ecosystem services provided by roadsides under a reduced mowing maintenance regimen—specifically stormwater filtration—are covered in the second chapter. The two other main benefits, which are mentioned but not covered in detail, are the conservation of RIDOT funds through a decrease in fuel consumption and the potential to significantly decrease the carbon footprint of RIDOT.

Rhode Island has 13,510 lane miles of publicly managed roads; state owned roads comprise 22% of this total (Dept. of Administration 2012), leaving the Rhode Island Department of Transportation (RIDOT) to manage nearly 3,000 lane miles.

With an average of four acres of managed roadside per lane mile in New England (Brown *et al.* 2011), RIDOT is responsible for maintaining nearly 3000 acres of roadside. With fuel consumption of flail mowers falling in the range of 0.41-1.46 gallons/acre (Sonntag *et al.* 2011) RIDOT is consuming 1,230-4,380 gallons of fuel. This estimate, however, is assuming all 3,000 acres are only mowed once. If calculations are made using hourly usage estimates (1.2-2.2 gallons/hour; Sonntag *et al.* 2011) RIDOT consumes 11,400-20,900 gallons of fuel in their conservatively estimated 9,500 mowing hours during the mowing season in single year (William Whelan pers. comm.). This amount of fuel usage is extremely expensive in terms of governmental funds, but this consumption also comes at a high price for the Ocean state's air quality. A typical flail mower produced nearly 22 kilograms of CO₂ per shoulder mile, and over 24 kilograms of CO₂ per hour (Sonntag *et al.* 2011). Using their hourly estimate of time spent mowing, RIDOT is producing nearly 230,000 kilograms of CO₂ emissions each mowing season.

Moving away from traditional mowing practices and towards reduced, low, and/or no mow practices is a trend nationwide. Many other states including Nebraska, Washington, Missouri, Minnesota, Wisconsin, Colorado, Iowa, New York, Utah, and Texas have included a reduction in mowing as part of their mowing policies (AASHTO 2004). In 2014, the Florida DOT reported that a sustainable vegetation management plan, which includes a reduction in mowing, would cut the state's vegetation management bill by 30 percent (Harrison 2014). The same report found that utilizing a sustainable vegetation management plan doubled the ecosystem services

economic value, gaining half a billion dollars. I believe that with an increase in reduce and now mow areas in Rhode Island, RIDOT can expect a similar economic return.

As natural landscapes decrease all over North America, it is vital and urgent that we are creative and opportunistic in where and how we choose to focus management efforts to best serve both the public and native plants and animals. One such innovation is ensuring roadsides and other highly constructed areas are providing as many ecosystem functions as possible while we mitigate their negative effects on the environment. These manuscripts provide insights on realistic ways to balance the requirement for human connectivity through linear construction with the need for habitat conservation and highlights opportunities for cost-savings and reductions in CO₂ emissions. I believe that these manuscripts will be important resources in future management decision and policy-making by federal, state, and local transportation agencies.

Appendix A: Additional Methods and Analysis Details:

Figure S1: Comparison of Fully Mowed (41.570447, -71.662369) and Reduce Mowed (41.751667, -71.464778) roadsides in Rhode Island.

Table S1: Road Characteristic related to invasive plant establishment

Road Side Characteristic	Description	Importance/relevance	Source
Soil Content	Taxonomic soil information (soil name, type and feature attributes) on the various types of soil as described by the Rhode Island Soil Survey Program, accessed from RIGIS (www.edc.uri.edu/rigis/data/)	Soil nutrients affect invasibility and the species that colonize an area.	Mortensen <i>et al.</i> 2009
Surrounding land use	Land cover classifications based on Anderson Level III modified coding, accessed from RIGIS. Examples of classifications include commercial, deciduous forests, residential, mixed forests, etc.	Undisturbed sites have a lower probability of invasive plants presence than areas which have undergone succession.	Mortensen <i>et al.</i> 2009, Irish <i>et al.</i> 1998
Hydrological condition	This includes characteristics of water condition within and around a site. These factors include, information about wetlands, size of drainage area, and amount of hydric soil (soils formed under saturated conditions which have formed anaerobic conditions)	These factors indicate the amount of time a given area experiences flooded condition which effects vegetation composition.	Kayhanian <i>et al.</i> 2002, Harbor 1994

Table S2: Site information. Percent of landuse and soil information is based on a buffer zone of 0.3 square miles around the GPS point taken for each site. The other percentages of landuses (other than forest and developed) are small and include agriculture, wetland, and vacant areas. Forested land includes all natural wooded areas, including forests (deciduous, mixed, and softwood) brushland. Developed land includes all residential (high, med, low residential use,) commercial, and industrial uses. Cec- Canton and Charlton fine sandy loams, Ud- Udorthents-Urban land complex, Ghd- Gloucester-Hinckley very stony sandy loams, Efa- Enfield silt loam, Cbd- Canton fine sandy loam, Pg- Pits, quarries, MU- Merrimac-urban land complex, CB- Canton-urban land complex.

Site ID	Community Type	AADT	Landuse most common to area	Most Common Soil Type	Hydric soils(m ²)
Site 1	Mowed	13,600-28,400	Roads (divided highways >200' plus related facilities and Deciduous Forest (>80% hardwood)	Cec	187885
Site 2	Mowed	10,600	Deciduous Forest (>80% hardwood)	Ud	69717
Site 3	Mowed	11,600	Medium High Density Residential (1/4 to 1/8 acre lots) and Deciduous Forest (>80% hardwood)	Ud	194243
Site 4	Mowed	14,700	Mixed Forest	Ghd and Efa	61794
Site 5	Mowed	16,400-29,201	Roads (divided highways >200' plus related facilities, followed by Deciduous Forest (>80% hardwood)	Ud and Cbd	111529
Site 6	Reduce	22900-	Roads	Ud	237211

	Mowed	34,000	(divided highways >200' plus related facilities		
Site 7	Reduce Mowed	22900-34,000	Roads (divided highways >200' plus related facilities	Ud	243469
Site 8	Reduce Mowed	22900-34,000	Roads (divided highways >200' plus related facilities	Pg	215673
Site 9	Reduce Mowed	18,800	Roads (divided highways >200' plus related facilities, followed by Deciduous Forest (>80% hardwood)	Pg	116611
Site 10	Reduce Mowed	18,800	Roads (divided highways >200' plus related facilities, followed by Deciduous Forest (>80% hardwood)	Pg and Ud	107835
Site 11	Wooded	16,400-29,200	Roads (divided highways >200' plus related facilities, followed by Deciduous Forest (>80%	Ud and MU	97318

			hardwood)		
Site 12	Wooded	16,400	Roads (divided highways >200' plus related facilities, followed by Deciduous Forest (>80% hardwood)	CB and MU	56676
Site 13	Wooded	20,100	Roads (divided highways >200' plus related facilities	Ud and MU	110414
Site 14	Wooded	20,100	Roads (divided highways >200' plus related facilities	Ud and MU	121437
Site 15	Wooded	16,400- 20,100	Roads (divided highways >200' plus related facilities, followed by Deciduous Forest (>80% hardwood)	MU	82603

Figure S2: Map of Roadside Sites in Rhode Island. Source for 'Roads' shape file: Rhode Island Geographic Information System

Figure S3: Box plot representing the difference of native species richness between mowing treatments at the 1000m² spatial scale.

Figure S4: Box plot representing the difference of native species richness between mowing treatments at the 100m² spatial scale.

Figure S5: Box plot representing the difference of introduced species richness between mowing treatments at the 100m² spatial scale.

Figure S6: Box plot representing the difference of introduced species richness between mowing treatments at the 10m² spatial scale.

Figure S7: Box plot representing the difference of native species richness between mowing treatments at the 1m² spatial scale.

Figure S8: Box plot representing the difference of introduced species richness between mowing treatments at the 1m² spatial scale.

Figure S9: Box plot representing the difference of introduced species richness between mowing treatments at the 1m² spatial scale.

Table S3: Results of one-way ANOVAs comparing total species richness, native species richness, introduced species richness, and invasive richness between Site Types (Fully Mowed, Reduce Mowed, Never Mowed) at four spatial scales: the entire 1000-m² plot, the 100-m² subplot, the two 10-m² subplots averaged across site, and the ten 1-m² subplots averaged across site.

Dependent Variable by Scale	Independent Variable	R²	Df	F	P	Range	Mean
Species Richness (1000-m ²)	Site Type	0.28	2, 12	3.69	0.056	52	44.47
	Fully-Reduced				0.341	52	39.6
	Reduced-Never				0.449	33	49.6
	Fully-Never				0.046 *	43	44.2
Native Richness (1000-m ²)	Site Type	0.75	2, 12	21.46	0.000 1*	38	27.27
	Fully-Reduced				0.171	28	19.8
	Reduced-Never				0.002 *	27	33
	Fully-Never				0.000 1*	38	29
Introduced Richness (1000-m ²)	Site Type	0.15	2, 12	2.27	0.146	25	17.27
	Fully-Reduced				0.797	25	19.8
	Reduced-Never				0.136	25	16.7
	Fully-Never				0.355	20	15.3
Invasive Richness (1000-m ²)	Site Type	0.04	2,12	1.26	0.318	5	3.4
	Fully-Reduced				0.383	5	3.2
	Reduced-Never				1.000	4	3.8
	Fully-Never				0.383	4	3.2
Species Richness (100-m ²)	Site Type	0.07	2, 12	0.54	0.596	16	21.67
	Fully-Reduced				0.989	16	20.8
	Reduced-Never				0.696	12	22.2
	Fully-Never				0.614	16	20.8
Native	Site Type	0.76	2, 12	23.12	<0.00	20	13.4

Dependent Variable by Scale	Independent Variable	R²	Df	F	P	Range	Mean
Richness (100-m ²)					01*		
	Fully-Reduced				0.158	11	10
	Reduced-Never				0.002*	17	16
	Fully-Never				<0.0001*	20	14.2
Introduced Richness (100-m ²)	Site Type	0.55	2, 12	9.71	0.003*	18	8.27
	Fully-Reduced				0.321	14	10.8
	Reduced-Never				0.038*	11	6.2
	Fully-Never				0.003*	14	7.8
Invasive Richness (100-m ²)	Site Type	0.16	2, 12	0.04	0.962	4	1.93
	Fully-Reduced				0.969	4	1.9
	Reduced-Never				1.000	3	2
	Fully-Never				0.969	2	1.9
Species Richness (10-m ²)	Site Type	0.16	2, 12	0.22	0.978	18	12.7
	Fully-Reduced				0.986	16	12.8
	Reduced-Never				0.978	18	12.75
	Fully-Never				0.999	18	12.55
Native Richness (10-m ²)	Site Type	0.69	2, 12	3.69	0.056	17	6.57
	Fully-Reduced				0.903	8	5.05
	Reduced-Never				0.130	17	7.45
	Fully-Never				0.063	17	7.2
Introduced Richness (10-m ²)	Site Type	0.56	2, 12	9.93	0.003*	12	6.13
	Fully-Reduced				0.962	12	7.75
	Reduced-Never				0.008*	12	5.3
	Fully-Never				0.005	11	5.35

Dependent Variable by Scale	Independent Variable	R²	Df	F	P	Range	Mean
					*		
Invasive Richness (10-m ²)	Site Type	0.10	2, 12	1.75	0.216	6	2.47
	Fully-Reduced				0.226	6	2.35
	Reduced-Never				0.946	5	2.8
	Fully-Never				0.355	4	2.25
Species Richness (1-m ²)	Site Type	0.17	2, 12	2.42	0.131	13	6.4
	Fully-Reduced				0.910	12	6.78
	Reduced-Never				0.136	12	6.21
	Fully-Never				0.259	11	6.02
Native Richness (1-m ²)	Site Type	0.35	2, 12	4.69	0.031 *	9	4.25
	Fully-Reduced				0.343	8	3.7
	Reduced-Never				0.283	9	4.79
	Fully-Never				0.025 *	9	4.27
Introduced Richness (1-m ²)	Site Type	0.75	2, 12	22.15	<0.00 01	9	3.95
	Fully-Reduced				0.683	9	4.99
	Reduced-Never				0.000 5*	8	3.28
	Fully-Never				0.000 1*	9	3.59
Invasive Richness (1-m ²)	Site Type	0.05	2, 12	0.67	0.532	4	1.47
	Fully-Reduced				0.821	4	1.55
	Reduced-Never				0.848	4	1.36
	Fully-Never				0.501	3	1.51
Native % Cover (1-m ²)	Site Type	0.03	2, 12	1.25	0.322	98	31.89
	Fully-Reduced				0.990	97	26.81
	Reduced-Never				0.425	98	34.81

Dependent Variable by Scale	Independent Variable	R²	Df	F	P	Range	Mean
	Fully-Never				0.358	98	34.01
Introduced % Cover (1-m ²)	Site Type	0.76	2, 12	23.16	<0.0001	99	28.38
	Fully-Reduced				0.941	99	40.08
	Reduced-Never				0.0003*	99	20.56
	Fully-Never				0.0002*	99	24.5
Invasive % Cover (1-m ²)	Site Type	0.01	2, 12	0.92	0.426	91	6.54
	Fully-Reduced				0.522	91	9.09
	Reduced-Never				0.994	74	3.52
	Fully-Never				0.464	91	6.94

*Indicates indicate significant differences in mean values between Site Types (Tukey's Test)

Table S4: Results of one-way ANOVAs comparing total species richness, native species richness, introduced species richness, invasive richness, native species percent cover, introduced species percent cover, and invasive species percent cover between Site Types (Fully Mowed, Reduce Mowed, Never Mowed) in subplots in clear zones and transition zones separately.

Dependent Variable and Zone	Independent Variable	R²	Df	F	P	Range	Mean
Species Richness, Clear Zone	Site Type	0.16	2, 12	0.02	0.983	21	8.33
	Fully-Reduced				0.983	19	8.37
	Reduced-Never				0.999	20	8.23
	Fully-Never				0.989	20	8.4
Native Richness, Clear Zone	Site Type	0.15	2, 12	2.23	0.149	19	4.24
	Fully-Reduced				0.810	10	4.53
	Reduced-Never				0.140	19	4.43
	Fully-Never				0.354	19	4.87
Introduced Richness, Clear Zone	Site Type	0.15	2, 12	2.19	0.145	13	3.82
	Fully-Reduced				0.744	13	4.53
	Reduced-Never				0.139	13	3.7
	Fully-Never				0.409	12	3.23
Invasive Richness, Clear Zone	Site Type	-0.16	2, 12	0.04	0.966	6	1.53
	Fully-Reduced				0.963	6	1.53
	Reduced-Never				0.990	6	1.5
	Fully-Never				0.990	6	1.57
Native % Cover, Clear Zone	Site Type	0.52	2, 12	8.63	0.005*	91	33.47
	Fully-Reduced				0.602	78	20.23
	Reduced-Never				0.005*	91	37.3
	Fully-Never				0.027*	91	42.88
Introduced % Cover, Clear Zone	Site Type	0.41	2, 12	5.77	0.018*	99.5	32.97
	Fully-Reduced				0.728	99.5	44.63
	Reduced-Never				0.018*	92.5	29
	Fully-Never				0.069	99.5	25.28
Invasive %	Site Type	0.01	2, 12	1.06	0.376	50	4.23

Dependent Variable and Zone	Independent Variable	R²	Df	F	P	Range	Mean
Cover, Clear Zone							
	Fully-Reduced				0.988	50	5.93
	Reduced-Never				0.485	18	1.35
	Fully-Never				0.407	50	5.43
Species Richness, Transition Zone	Site Type	0.20	2, 12	2.77	0.103	17	7.16
	Fully-Reduced				0.806	14	7.8
	Reduced-Never				0.098	17	6.99
	Fully-Never				0.265	17	6.68
Native Richness, Transition Zone	Site Type	0.46	2, 12	6.94	0.01*	16	3.64
	Fully-Reduced				0.137	8	2.96
	Reduced-Never				0.266	16	4.39
	Fully-Never				0.008*	16	3.59
Introduced Richness, Transition Zone	Site Type	0.58	2, 12	10.59	0.002*	10	3.18
	Fully-Reduced				0.873	10	4.36
	Reduced-Never				0.008*	10	2.48
	Fully-Never				0.003*	10	2.7
Invasive Richness, Transition Zone	Site Type	0.13	2, 12	2.03	0.17	4	0.77
	Fully-Reduced				0.303	4	0.93
	Reduced-Never				0.932	4	0.52
	Fully-Never				0.178	4	0.86
Native % Cover, Transition Zone	Site Type	-0.09	2, 12	0.396	0.682	98	30.82
	Fully-Reduced				0.929	97	27.85
	Reduced-Never				0.863	98	33.46
	Fully-Never				0.659	98	31.14
Introduced % Cover,	Site Type	0.67	2, 12	15.43	0.0005*	100	27.26

Dependent Variable and Zone	Independent Variable	R²	Df	F	P	Range	Mean
Transition Zone							
	Fully-Reduced				0.749	100	38.99
	Reduced-Never				0.002*	100	18.46
	Fully-Never				0.0007*	100	24.33
Invasive % Cover, Transition Zone	Site Type	-0.01	2, 12	0.90	0.432	91	7.11
	Fully-Reduced				0.534	91	9.88
	Reduced-Never				0.991	74	4.06
	Fully-Never				0.465	91	7.4

*Indicates indicate significant differences in mean values between Site Types (Tukey's Test)

Table S5: Results of non-parametric Wilcoxon-Mann-Whitney test comparing the mean of total species richness, native species richness, introduced species richness, invasive species richness, native species cover, introduced species cover, and invasive species cover between all subplots within the clear zone to all the subplots in the transitional zone.

Dependent Variable	Site Types Included	Independent Variable	P
Species Richness	All Sites	Zone	0.367
Native Richness	All Sites	Zone	0.533
Introduced Richness	All Sites	Zone	0.238
Invasive Richness	All Sites	Zone	0.019*
Native % Cover	All Sites	Zone	0.696
Introduced % Cover	All Sites	Zone	0.159
Invasive % Cover	All Sites	Zone	0.602
Species Richness	Fully Mowed	Zone	0.606
Native Richness	Fully Mowed	Zone	0.022*
Introduced Richness	Fully Mowed	Zone	0.327
Invasive Richness	Fully Mowed	Zone	0.71
Native % Cover	Fully Mowed	Zone	0.912
Introduced % Cover	Fully Mowed	Zone	0.846
Invasive % Cover	Fully Mowed	Zone	0.959
Species Richness	Reduce Mowed	Zone	0.577
Native Richness	Reduce Mowed	Zone	0.056
Introduced Richness	Reduce Mowed	Zone	0.698
Invasive Richness	Reduce Mowed	Zone	0.158
Native % Cover	Reduce Mowed	Zone	0.104
Introduced % Cover	Reduce Mowed	Zone	0.065
Invasive % Cover	Reduce Mowed	Zone	0.119
Species Richness	Never Mowed	Zone	0.074
Native Richness	Never Mowed	Zone	0.856
Introduced Richness	Never Mowed	Zone	<0.0001*
Invasive Richness	Never Mowed	Zone	0.022*
Native % Cover	Never Mowed	Zone	0.025*
Introduced % Cover	Never Mowed	Zone	0.013*
Invasive % Cover	Never Mowed	Zone	0.453

*Indicates indicate significant differences in mean values between Site Types (Tukey's Test)

APPENDICES MANUSCRIPT 2

Appendix B: Additional analysis details

Table S1: Results of Tukey's HSD post hoc for time period and site factorial ANOVAs for Cd, Cu, and NO₃.

Pollutant	Time Period: Site	p-value
Cd	September:6-August:5	0.0001
Cd	September:6-September:1	0.0001
Cd	September:6-October:3	0.0001
Cd	August:15-September:6	0.0001
Cd	September:6-August:1	0.000155
Cd	September:5-August:5	0.002584
Cd	September:6-October:5	0.003706
Cd	August:5-September:3	0.006786
Cd	September:6-October:2	0.008818
Cd	September:5-September:1	0.010272
Cd	July:12-August:5	0.017716
Cd	July:15-August:5	0.018738
Cd	September:5-August:3	0.021777
Cd	September:6-July:6	0.023052
Cd	September:3-September:1	0.024026
Cd	August:15-September:5	0.025655
Cd	October:8-August:5	0.029529
Cd	September:5-August:1	0.040769
Cd	October:3-September:3	0.048972
Cd	August:12-August:5	0.052502
Cd	July:12-September:1	0.053137
Cu	July:4-September:3	0.0001
Cu	September:3-October:2	0.0001
Cu	August:4-September:3	0.0001
Cu	October:4-September:3	0.0003
Cu	September:4-July:4	0.0003
Cu	August:7-July:4	0.0004
Cu	September:4-October:2	0.0005
Cu	July:4-September:1	0.0005
Cu	September:4-August:4	0.0006
Cu	August:7-October:2	0.0007

Cu	August:7-August:4	0.0009
Cu	October:2-September:1	0.0010
Cu	August:4-September:1	0.0012
Cu	October:4-September:4	0.0013
Cu	September:8-July:4	0.0017
Cu	September:15-July:4	0.0018
Cu	August:7-October:4	0.0019
Cu	October:4-September:1	0.0025
Cu	September:12-July:4	0.0026
Cu	September:8-October:2	0.0031
Cu	September:15-October:2	0.0033
Cu	September:8-August:4	0.0039
Cu	September:15-August:4	0.0041
Cu	September:12-October:2	0.0046
Cu	July:4-August:2	0.0055
Cu	September:12-August:4	0.0058
Cu	September:8-October:4	0.0076
Cu	September:15-October:4	0.0080
Cu	October:2-August:2	0.0094
Cu	September:12-October:4	0.0111
Cu	August:4-August:2	0.0117
Cu	July:4-July:2	0.0123
Cu	July:4-September:2	0.0168
Cu	October:2-July:2	0.0206
Cu	October:4-August:2	0.0217
Cu	August:4-July:2	0.0251
Cu	October:2-September:2	0.0277
Cu	August:8-July:4	0.0291
Cu	August:4-September:2	0.0336
Cu	October:4-July:2	0.0445
Cu	August:8-October:2	0.0466
Cu	July:15-July:4	0.0469
NO ₃	October:15-August:7	0.02825
NO ₃	October:15-October:7	0.02825
NO ₃	October:15-September:2	0.02825
NO ₃	October:15-August:3	0.028251
NO ₃	October:15-September:3	0.028251
NO ₃	October:15-October:3	0.028253
NO ₃	October:15-August:1	0.028253
NO ₃	October:15-October:2	0.028264

NO ₃	October:15-August:12	0.0286
NO ₃	October:15-September:4	0.028724
NO ₃	October:15-September:6	0.028952
NO ₃	October:15-October:12	0.029094
NO ₃	October:15-August:8	0.029219
NO ₃	October:15-October:1	0.032283
NO ₃	October:15-September:15	0.034186
NO ₃	October:15-July:8	0.035468
NO ₃	October:15-October:8	0.03702
NO ₃	October:15-September:7	0.040692
NO ₃	October:15-July:12	0.040692
NO ₃	October:15-July:15	0.040697
NO ₃	October:15-September:1	0.040787
NO ₃	October:15-October:4	0.044244
NO ₃	October:15-July:5	0.045155
NO ₃	October:15-August:6	0.049112
NO ₃	October:15-August:4	0.052758
NO ₃	October:15-September:8	0.052852

Figure S1: Boxplot representing the difference in aluminum (Al) concentrations accumulated by ion-exchange resin membranes at the two distances from the roadside pavement.

Figure S2: Boxplot representing the difference in Manganese (Mn) concentrations accumulated by ion-exchange resin membranes at the two distances from the roadside pavement.

Figure S3: Boxplot representing the difference in Zinc (Zn) concentrations accumulated by ion-exchange resin membranes at the two distances from the roadside pavement.

Figure S4: Boxplot representing the difference in Iron (Fe) concentrations accumulated by ion-exchange resin membranes in roadsides under two different mowing treatments.

Table S2: Range and Mean calculations for each pollutant measured. 390 total measurements were taken for each ion.

Pollutant	Range	Mean (ppm)
Al	6.8	1.27
Cd	0.012	0.007
Cu	0.137	0.02
Fe	3.4	0.51
Mg	49.2	3.17
Mn	3.1	0.17
Ni	0.36	0.034
P	54.1	1.93
Pb	0.22	0.04
Zn	0.3	0.03
NH ₄	109140	3557.1
NO ₃	51770	5060.7

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