# FINAL REPORT WY2304F

# REVEGETATION SUCCESS AND WEED RESILIENCE OF WYOMING RIGHT-OF-WAY RECLAMATION

March 2023

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| 1. Report No.<br>WY2304F | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle<br>Revegetation Success and Weed Resilience of Wyoming Right-Of-Way Reclamation | | 5. Report Date<br>March 2023<br>6. Performing Organization Code |
| 7. Author(s)<br>Kristina Hufford, Ph.D. ORCID 0009-0008-6871-7258<br>Joellyn Moine ORCID 0009-0002-9286-7877<br>R. Scott Gamo, Ph.D. ORCID 0000-0001-8672-3485 | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>University of Wyoming<br>Department of Ecosystem Science and Management<br>1000 E University Ave<br>Laramie, WY 82071 | | 10. Work Unit No.<br>11. Contract or Grant No.<br>RS02218 |
| 12. Sponsoring Agency Name and Address<br>Wyoming Department of Transportation<br>5300 Bishop Blvd. Bldg. 6100<br>Cheyenne, WY 82009 | | 13. Type of Report and Period Covered<br>Final Report<br>14. Sponsoring Agency Code |
| 15. Supplementary Notes<br>WYDOT Contact: Scott Gamo | | |

**16. Abstract**

Roadside revegetation within highway rights-of-way is a final step in road construction, and often occurs in areas that are difficult to reclaim due to harsh climate conditions and impacts of land disturbance, including topsoil removal, soil compaction, and the presence of noxious and invasive weeds. Wyoming Department of Transportation managers have focused on reseeding native plant species since the 1990s, and seed mixes are designed for application among six Level II ecoregions across the state. A study of 73 sites along 12 highways in central and southern Wyoming revealed that 36 percent of seeded species were present among sampled sites between two and twenty years after projects were completed. In addition, a minimum of one seeded species was detected along transects for all 31 roadside projects. Grasses were the most likely plant type to establish from seed mixes despite both the number of forbs in seed mixes, and the large number of native and non-native forbs present at field sites. While many seeded species were not detected along reclaimed roadsides, a higher abundance of seeded plants corresponded to a significantly lower number of introduced weeds. Moreover, a higher number of weeds along roadsides positively correlated with a higher number of weeds over the fence line, providing evidence that weeds may be spreading along road corridors and into nearby, undisturbed rangeland. Results of this study support seeding roadsides with native vegetation to minimize the number and abundance of undesirable, non-native species. Further study is needed to determine the factors that prevent establishment of seeded forbs along road rights-of-way in Wyoming.

| 17. Key Words<br>Wyoming, Revegatation, Rights-of-Way, Noxious and Invasive Weeds, Seed species | 18. Distribution Statement<br>This document is available through the National Transportation Library and the Wyoming State Library. Copyright ©2018. All rights reserved. State of Wyoming, Wyoming Department of Transportation, and the University of Wyoming. | | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>Non-Classified | 20. Security Classif. (of this page)<br>Non-Classified | 21. No. of Pages<br>XX | 22. Price |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

## SI* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |

### APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/$in^2$ |

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**Executive Summary**

Roadside revegetation within highway rights-of-way (ROW) is a final step in road construction and often occurs in areas that are difficult to reclaim due to harsh climate conditions and impacts of land disturbance, including topsoil removal, soil compaction, and the presence of noxious and invasive weeds. In Wyoming, Department of Transportation managers have focused on reseeding native plant species since the 1990s, and seed mixes are designed for application among six Level II ecoregions across the state. This seeding approach was developed to enhance seeding success of ROWs and potentially minimize weedy species through natural competition.

The study evaluated 73 sites along 12 highways in central and southern Wyoming and used statistical analyses to compare seeded native ROW vegetation to native rangeland vegetation found on relatively undisturbed adjoining sites. Data collected included species composition and abundance, and characteristics of vegetation structure such as plant height. Analyses included t-tests and multi-factor analysis of variance (ANOVA) to compare differences between ROW and control (adjacent) sites, and regression analyses to find relationships between relative presence of native and weed species. The study revealed that 36% of seeded species were present among sampled ROW sites between two and twenty years after projects were completed. In addition, a minimum of one seeded species was detected along transects for all 31 roadside projects associated with the sampled sites. Grasses were the most likely plant type to establish from seed mixes despite both the number of forbs in seed mixes, and the large number of native and non-native forbs present at field sites. While many seeded species were not detected along reclaimed roadsides, a higher abundance of one or more seeded species corresponded to a significantly lower number of introduced weeds. Moreover, a higher number of weeds along roadsides positively correlated with a higher number of weeds over the fence line, providing evidence that weeds may be spreading along road corridors and into nearby, undisturbed rangeland.

Results of this study support seeding roadsides with native vegetation to minimize the number and abundance of undesirable, non-native species. Ultimately the study recommends the continued use of native species in reclamation seed mixes and suggest additional effort be provided at enhancing planted species establishment to further reduce invasive and weed species impacts. This information should be useful to Wyoming and other states that utilize or intend to utilize ROW seed mixes dominated with native species.

# Chapter 1. Introduction

Right-of-way vegetation strips including road ditches represent significant acreage along roadways in Wyoming and affect a wide range of habitats (Omernik 1987). The Wyoming Department of Transportation (WYDOT) is responsible for maintaining approximately 6,700 miles of roadways including the vegetation within the right-of-way along each road corridor (WYDOT 2015). Ecological impacts of road construction are mitigated by land reclamation, and WYDOT is required to reseed roadsides after construction to stabilize exposed surfaces, minimize soil erosion and maintain visibility, as well as limit the spread of undesirable species. Roadside revegetation is a final step in road construction, and often occurs in areas that are difficult to reclaim due to harsh climate conditions and impacts of previous land disturbance, including topsoil removal, soil compaction, and the presence of noxious and invasive weeds (Forman 1998; Tinsley et al. 2006; Hillhouse et al. 2018).

Road corridors are vulnerable to introductions of undesirable species and serve as a first line of defense to limit biological invasion in adjacent federal, state, and private rangelands (Hansen and Clevenger 2005; Von der Lippe and Kowarik 2007). Roadside vegetation may also influence factors such as attractiveness to wildlife and livestock, and may be managed to reduce potential traffic safety concerns. WYDOT managers have focused on reseeding commercially available native, rather than introduced, plant species along roadways since the 1990s, and seed mixes are designed to be appropriate for application among six Level II ecoregions in the state (WYDOT 2013; FHA 2017). WYDOT reseeding practices aim to establish resilient, native plant communities beneficial to rangelands and residents in Wyoming, but long-term success rates have not been evaluated. There is a need for comprehensive assessment of the effectiveness of different seed mixes for: 1) the establishment of desirable native plant communities, and 2) the reduction of noxious and invasive weeds. Alien species alone result in environmental costs of more than $120 billion per year in the United States, and different revegetation strategies can alter the number and impact of invasive weeds (Pimentel et al. 2005). An evaluation of the effectiveness of seeding treatments and associated reclamation factors may therefore guide reclamation planning and assist in the development of cost-effective roadside revegetation practices in Wyoming.

### 1.1 Study goal and methodology

Our objectives were to evaluate different reclamation seed mixes over the years to determine the rate of reseeding success and better define combinations of species and site variables that contribute to successful revegetation outcomes. We also compared sites and seed mixes for resilience to invasion by high impact species, such as cheatgrass. Data and results will contribute to recommendations to maximize seeding success and minimize weeds, and will assist future evaluations of other vegetation factors, such as minimizing traffic/wildlife conflicts.

## Chapter 2. Literature Review

Roadside vegetation within highway rights-of ways (ROW) contributes to environmental health and evidence suggests that vegetation strips control runoff, improve soil conservation, and may support a wide range of pollinators and some wildlife (Hopwood 2008; Bissonette and Rosa 2009; McCleery et al. 2015; New et al. 2021). Vegetation benefits, however, are often reduced by the presence of weeds, such as cheatgrass *(Bromus tectorum*), and growing evidence suggests roadways serve as corridors for the spread of invasive species (Christen and Matlack 2009). A study of 42 roadways in Utah found a 50 percent increase in exotic species and three times the cover of cheatgrass along paved roads (Gelbard and Belnap 2003). In a separate study in Canada, paved roads not only served as conduits for invasive species, but were also linked to the spread of alien plants in adjacent, undisturbed rangeland (Hansen and Clevenger 2005). Remote sensing analysis of the North American Great Basin determined that cheatgrass was 13 percent more likely to be found within 700 m of roadways (Bradley and Mustard 2006). In most cases, alien species were more likely to occur near paved roads that supported higher traffic volume when compared to low traffic volume or non-paved roadways, with resulting negative impacts for nearby wildlands (e.g., Joly et al. 2011; Lázaro-Lobo and Ervin 2019).

Despite the correlation between road corridors and the spread of invasive species, few studies have determined the efficacy of reclamation for reducing the frequency and occurrence of invasive weeds. Huntsman (2011) found one third fewer introduced species along revegetated roadways in Australia relative to sites that were not planted. Tinsley et al. (2006) studied outcomes of three seed mixes planted along roadsides in Texas, but did not compare results with the levels of weed infestation at seeded sites. An experimental study of herbicide and seeding treatments along roads in Glacier National Park found no effect of native seeding on exotic species cover (Tyser et al. 1998), while seed addition did improve native species abundance in experimental plots in Iowa (Martin and Wilsey 2006). These studies rarely address roadway seeding outcomes for weed control and no research is yet published to compare roadside seeding with weed density in Wyoming.

ROW vegetation strips represent significant acreage along roadways in Wyoming and affect a wide range of habitats (Omernik 1987).  WYDOT is responsible for maintaining approximately 6,700 miles of roadways, including the vegetation within the adjoining ROW along each road corridor (WYDOT 2015).  Ecological impacts of road construction are mitigated by land reclamation, and WYDOT is required to reseed roadsides after construction to stabilize exposed surfaces, minimize soil erosion and maintain visibility, as well as limit the spread of undesirable species.  Roadside revegetation is a final step in road construction, and often occurs in areas that are difficult to reclaim due to harsh climate conditions and impacts of previous land disturbance, including topsoil removal, soil compaction, and the presence of noxious and invasive weeds (Forman 1998; Tinsley et al. 2006; Hillhouse et al. 2018).

Given that road corridors are vulnerable to introductions of undesirable species, roadside revegetation and subsequent management may serve as a first line of defense to limit biological invasion in adjacent federal, state, and private rangelands (Hansen and Clevenger 2005; Von der Lippe and Kowarik 2007). WYDOT managers have focused on reseeding commercially available native plant species rather than introduced species along roadways since the 1990s, and seed mixes are designed to be appropriate for application among six Level II ecoregions in the state (WYDOT 2013; FHA 2017).  WYDOT reseeding practices aim to establish resilient, native plant communities beneficial to rangelands and residents in Wyoming, but long-term success rates of roadside revegetation have not been evaluated.

## Chapter 3. Data Collection and Descriptive Statistics

### 3.1 Results and Discussion

#### 3.1.1 Seed Mix Outcomes

The 73 sample sites comprised 31 roadway projects that underwent revegetation via seeding. No seed mix was represented more than three times in sampling. Combined seed mix species were weighted heavily in favor of grasses (0.69) with a smaller proportion of mixes dedicated to forbs (0.18) and shrubs (0.13). The average number of species in a seed mix was 7.5 with a maximum of 12 and a minimum of 3 species seeded along roadways. Regression analysis indicated a significant increase in the total number of species included in seed mixes for roadside reseeding over the span of 19 years (Fig. 2; $F_{1,71} = 34.78$, $p = 0.0001$).

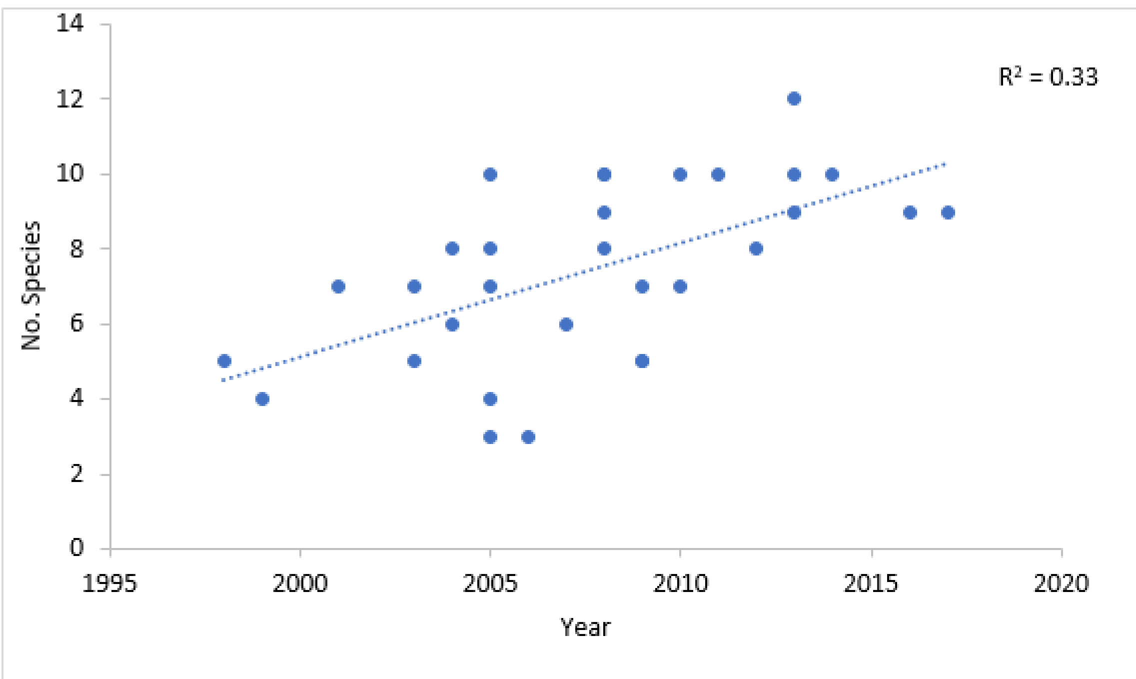


**Figure 1. The number of species in the seed mix for 31 roadway revegetation projects spanning 19 years and representing sites sampled along 12 highways in central and southern Wyoming**

Seed mixes for all sites totaled 42 unique species (Table 1) consisting of native plants with few exceptions; *Thinopyrum intermedium* (intermediate wheatgrass), *Festuca ovina* (sheep fescue), and *Medicago sativa* (yellow alfalfa) occurred in one mix each, and *Astragalus cicer* (cicer milkvetch) occurred in three mixes. In addition, *Erysimum ×marshallii* (Siberian wallflower) is a hybrid often considered non-native and was included in one mix. None of the five non-native, seeded species were detected in transect sampling.

Of the 38 native species used in reseeding, 8 were included in 10 or more seed mixes. These were *Poa secunda* (Sandberg bluegrass), *Achnatherum hymenoides* (Indian ricegrass), a combined *Elymus* species category (representing thickspike and slender wheatgrass), *Pseudoroegneria spicata* (bluebunch wheatgrass), *Pascopyrum smithii* (western wheatgrass), *Elymus elymoides* (bottlebrush squirreltail), *Krascheninnikovia lanata* (winterfat), and *Achillea millefolium* (western yarrow). Only 15 seed mix species were detected in road transects, including all 8 of the most common, planted species (Fig. 3). Seven of those species were also common in control transects, with only *Achillea millefolium* absent. An average of 2.8 and 2.6 seed mix species occurred in roadside and control transects, respectively, with a minimum of zero and maximum of six seed mix species for all transects. Two roadside sites showed no signs of seed mix species, although a minimum of one species in the seed mix occurred in all roadside projects when we pooled sites that shared the same seed mix. Overall, 15 of 42 or 36 percent of seed mix species were present at one or more sampled road sites. Approximately 64 percent of planted species were not detected in field samples, indicating that these species did not establish, originally established but did not survive over time, or were present but were not found along transects or in the surrounding 10 m area.

Regression of the project initiation date and the number of seed mix species detected along roads in transects was not significant, suggesting that successful seeding along roadsides at sampled sites did not depend on the year seeds were planted or the time since planting. There was a significant positive correlation between the proportion of species in the seed mix detected along roadsides and in nearby control sites ($R^2 = 0.10$, $p = 0.006$). This result suggested that successful species planted along roads either closely resembled control sites, or dispersed into nearby, undisturbed rangeland. It is also possible some species dispersed into the roadway from control sites. Lastly, the proportion of seed mix species detected in road transects was heavily weighted in favor of grasses (0.93), while seeded forbs (0.02) and shrubs (0.05) were uncommon.

### 3.1.2 Species Diversity and Introduced Weeds

Field transects yielded a total of 92 identifiable species (including the *Elymus* category) of which 22 were introduced or non-native (Appendix A; Fig. 4). Most of the identified species were forbs (0.60) with the remaining representing grasses (0.22), shrubs (0.14), and other graminoids (*Carex* and *Juncus* spp.; 0.04). The subset of 22 introduced species consisted solely of grasses (0.36) and forbs (0.64). The average number of species did not differ significantly between roadside and control transects (6.55 control vs. 6.51 roadside; $p = 0.91$), but did differ significantly for the number of introduced and native species (Fig. 5). Control transects in nearby rangeland had a significantly greater number of native species when compared to roadsides, while roadside transects had a significantly greater number of introduced species when compared to undisturbed control sites ($p < 0.0001$).

Table 1 is the key for species in the roadside seed mixes, including their USDA Plants Database symbol, status (native or introduced), and life form. It also lists the Elymus category to account for seed mix and related species that were difficult to separate with accuracy along roadsides.

**Table 1. USDA Plants Database key for species in the roadside seed mixes**

| Symbol | Species | Status | Life Form |
|---|---|---|---|
| ACHY | *Achnatherum hymenoides* | Native | Grass |
| ACMI2 | *Achillea millefolium* | Native | Forb |
| ARFR4 | *Artemisia frigida* | Native | Shrub |
| ARTR2 | *Artemisia tridentata* | Native | Shrub |
| ASCI4 | *Astragalus cicer* | Introduced | Forb |
| ATCA2 | *Atriplex canescens* | Native | Shrub |
| ATGA | *Atriplex gardneri* | Native | Shrub |
| BOCU | *Bouteloua curtipendula* | Native | Grass |
| BOGR2 | *Bouteloua gracilis* | Native | Grass |
| BRMA4 | *Bromus marginatus* | Native | Grass |
| CALO | *Calamovilfa longifolia* | Native | Grass |
| CHVI8 | *Chrysothamnus viscidiflorus* | Native | Shrub |
| CLSE | *Cleome serrulata* | Native | Forb |
| ELEL5 | *Elymus elymoides* | Native | Grass |
| Elymus | Includes *Elymus lanceolatus* and *Elymus trachycaulus* | Native | Grass |
| ERMA17 | *Erysimum ×marshallii* | Introduced* | Forb |
| ERNA10 | *Ericameria nauseosa* | Native | Shrub |
| FEOV | *Festuca ovina* | Introduced | Grass |
| GAAR | *Gaillardia aristata* | Native | Forb |
| GAPU | *Gaillardia pulchella* | Native | Forb |
| KOMA | *Koeleria macrantha* | Native | Grass |
| KRLA2 | *Krascheninnikovia lanata* | Native | Shrub |
| LECI4 | *Leymus cinereus* | Native | Grass |

| | | | |
|---|---|---|---|
| LETR5 | *Leymus triticoides* | Native | Grass |
| LILE3 | *Linum lewisii* | Native | Forb |
| MATA2 | *Machaeranthera tanacetifolia* | Native | Forb |
| MESA | *Medicago sativa* | Introduced | Forb |
| NAVI4 | *Nassella viridula* | Native | Grass |
| PASM | *Pascopyrum smithii* | Native | Grass |
| PEEA | *Penstemon eatonii* | Native | Forb |
| PEPA8 | *Penstemon palmeri* | Native | Forb |
| PEST2 | *Penstemon strictus* | Native | Forb |
| POSE | *Poa secunda* | Native | Grass |
| PSSP6 | *Pseudoroegneria spicata* | Native | Grass |
| RACO3 | *Ratibida columnifera* | Native | Forb |
| RHTR | *Rhus trilobata* | Native | Forb |
| SCSC | *Schizachyrium scoparium* | Native | Grass |
| SPAI | *Sporobolus airoides* | Native | Grass |
| SPCO | *Sphaeralcea coccinea* | Native | Forb |
| SPCR | *Sporobolus cryptandrus* | Native | Grass |
| SPGR2 | *Sphaeralcea grossulariifolia* | Native | Forb |
| THIN6 | *Thinopyrum intermedium* | Introduced | Grass |

* *Erysimum ×marshallii*, or Siberian wallflower, is a hybrid species and its status is not available at the USDA Plants Database. For purposes of this study, it is categorized as introduced.

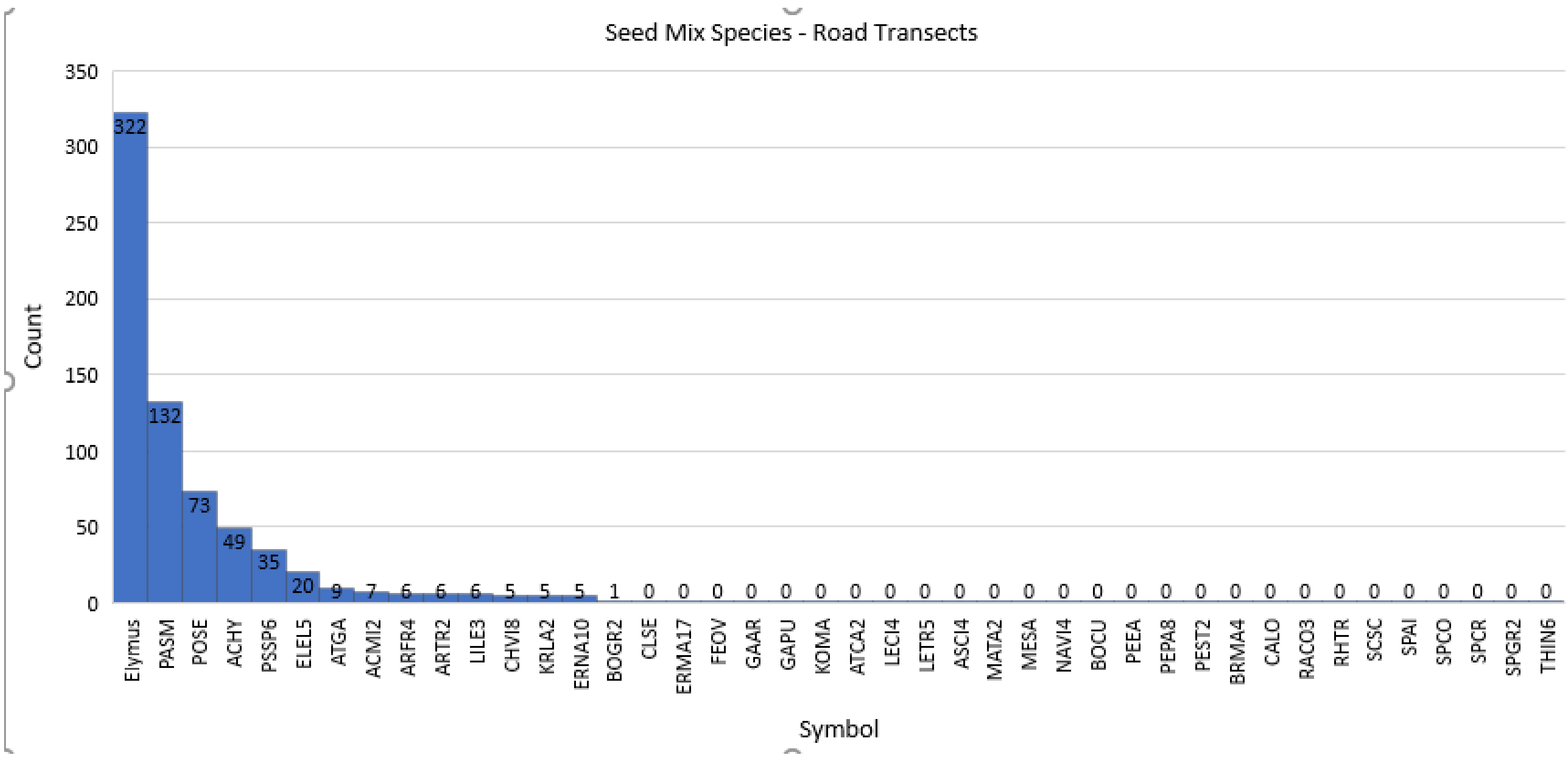


**Figure 2. The total number of each of 42 seed mix species detected in road transects at 73 sites along 12 Wyoming highways**

In addition, the average number of individual plants, regardless of species number, was greater along roadsides but did not significantly differ between control and roadside transects (28.4 control vs. 31.4 roadside; $p = 0.06$). The total number of introduced and native plants, however, was significantly different (Fig. 6; $p < 0.0001$), with roadsides representing larger numbers of introduced plants and smaller numbers of native plants relative to control sites.

The most common, non-native species recorded in roadside transects was *Agropyron cristatum* (AGCR), or crested wheatgrass. Crested wheatgrass was intentionally planted for erosion control along roadsides in North America beginning in the mid-1930s, but fell out of favor once studies revealed growing evidence of ecological impacts, including invasive monocultures, declining native plant diversity, and the loss of wildlife habitat (McWilliams and Van Cleave 1960; Henderson and Naeth 2005). Many recent roadside projects reconstruct sites that were originally planted with crested wheatgrass. As a result, sites recently revegetated with a native seed mix may also include a significant number of *Agropyron* spp., particularly near the fence line where original plantings are less likely to be disturbed. The second most common non-native species recorded along roads was *Bromus tectorum* (BRTE), or cheatgrass. Cheatgrass was mistakenly introduced to North America in the 1800s and has since spread widely in the western United States (Novak and Mack 2001). Cheatgrass is an aggressive invader with significant impacts to native ecosystems, including accelerated fire regimes (Bradley et al. 2018). Other common weeds included *Alyssum alyssoides* (ALAL3; pale madwort), *Bromus inermis* (BRIN2; smooth brome), *Alyssum desertorum* (ALDE; desert madwort), and *Melilotus officinalis* (MEOF; sweet clover).

### 3.1.3 Patterns of Native and Non-native Diversity

To test the hypothesis that larger numbers of invasive weeds along roadsides correspond with larger numbers of weeds in nearby rangeland, we conducted linear regression analyses for the number of introduced species, or the abundance (counts) of introduced plants, detected in road and control transects. We found a positive relationship in each regression analysis (Fig. 7). Greater numbers of introduced species along roadsides corresponded to greater numbers of introduced species in control sites ($F_{1, 71} = 4.93$, $p = 0.03$). Higher numbers of introduced plants (regardless of the number of species) in road transects correlated with higher numbers of introduced plants in control transects as well ($F_{1, 71} = 4.79$, $p = 0.03$). The coefficient of determination was relatively low ($R^2 = 0.06$) in each analysis, however, due to the number of sites where weed diversity and abundance along roads did not correspond to weed diversity and abundance (count = 0) in nearby, undisturbed rangeland. The dispersal of weedy species away from roads may be impeded in some environments.

As a last step, we tested the relationship between the total number of seed mix plants and the total number of introduced plants found along roadsides (Fig. 8). Results indicated a strong negative correlation between the number of weeds and the abundance of seed mix plants regardless of the number of seed mix species present at each site ($F_{1, 71} = 19.85$; $p < 0.0001$). This result supports the hypothesis that successful seeding corresponds with a lower number of weeds, possibly a result of competition among seeded species and the non-native, weed soil seed bank. Data were transformed prior to analyses if needed and transect length adjustments to account for some shorter transects along roadsides did not change outcomes of any of the comparisons of native and non-native species.

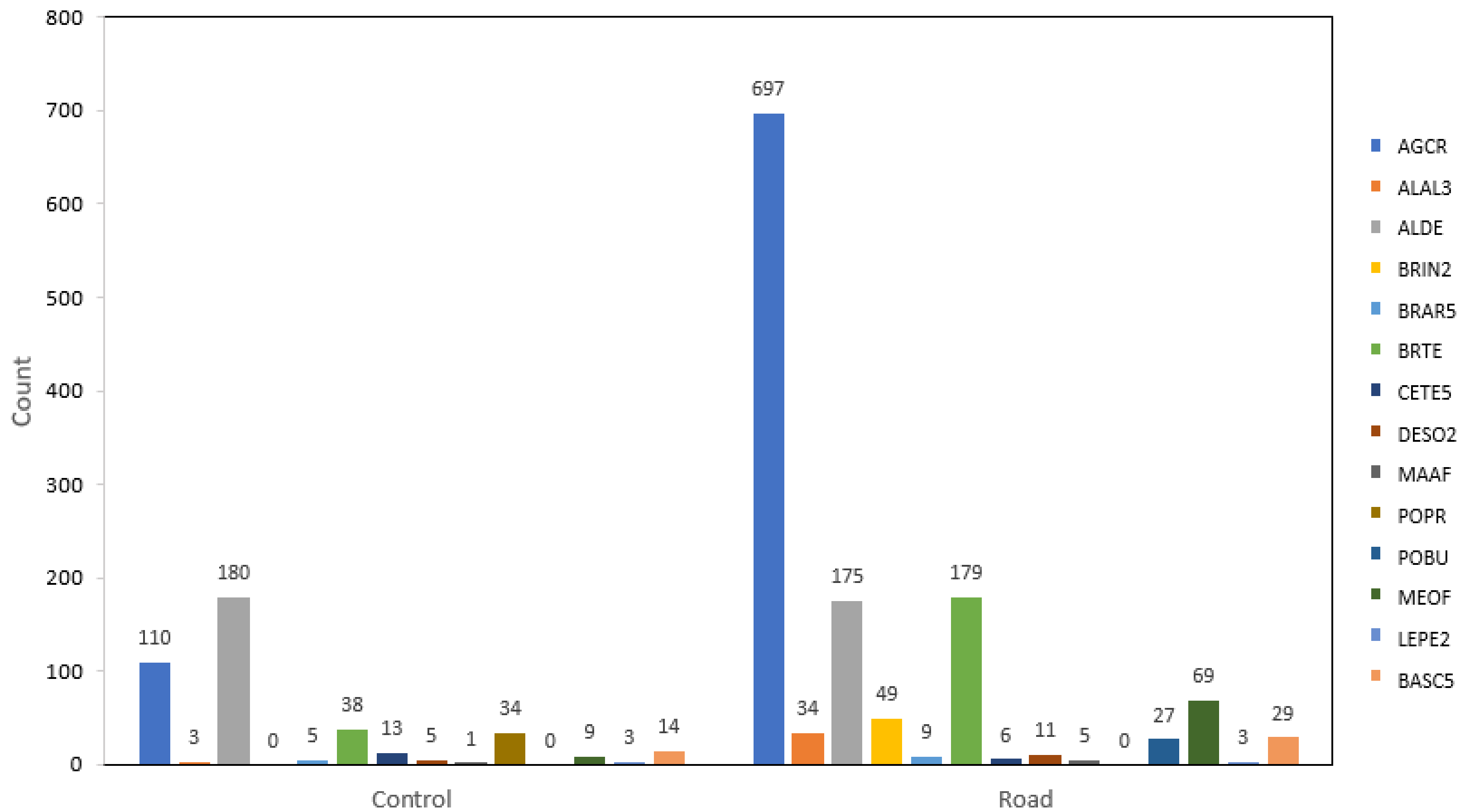


**Figure 3. Counts of introduced species common in control and roadside transects where the total number of plants combined across all transects was 6 or greater at 73 sites along 12 Wyoming highways**

### 3.1.4 Plant Height

To assess vegetation structure,we compared the average height of shrubs, forbs, and grasses between roadside and control sites, and shrub height was significantly greater in undisturbed rangeland when compared to shrubs growing along roads ($F_{1, 144} = 5.74$, $p = 0.018$). Forb height did not differ between roadside and control transects ($F_{1, 144} = 3.16$, $p = 0.08$), while grasses were significantly taller along roadsides relative to control sites ($F_{1, 144} = 43.98$, $p < 0.0001$). In each case, data were $log_{10}$-tranformed prior to analyses, and the road bearing (divided into east-west and north-south corridors) did not significantly impact results. We note that transect data were collected prior to annual roadside mowing in 2019.

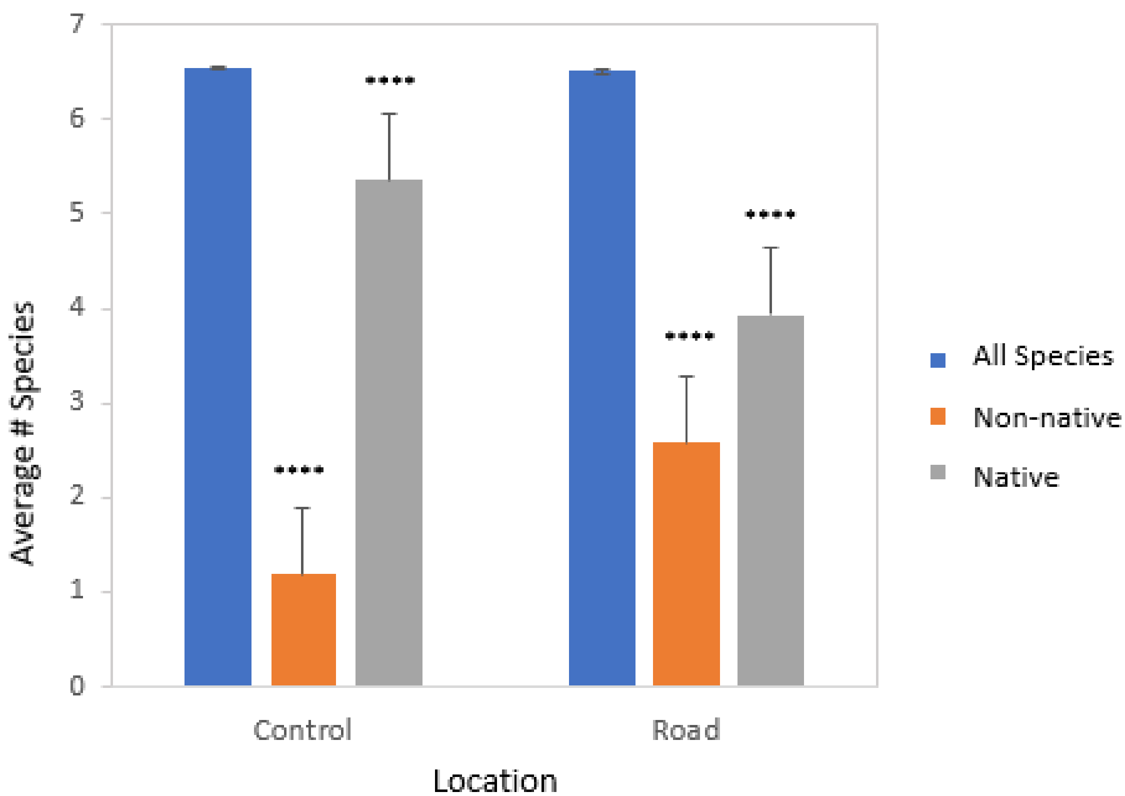


**Figure 4. The average number of species and the average number of non-native and native species detected in control and road transects along 12 highways at 73 sites in Wyoming (**** p < 0.001, standard error bars represent +1)**

### 3.1.5 Foliar Cover and Soil Surface

Roadsides had greater levels of vegetative cover than control sites for estimates of foliar cover, the proportion of the top canopy layer calculated along transects ($F_{1, 144}$=12.03, $p < 0.0001$). Similarly, roadsides had lower counts of "no foliar cover" (top layer code of "N") following Assessment, Inventory and Monitoring protocols ($F_{1, 144}$=17.22, $p < 0.0001$; Herrick et al. 2016). Herbaceous litter (HL; including non-living, detached stems, roots, and leaves) was also greater along roadsides than control sites ($F_{1, 144}$=30.26, $p < 0.0001$). Despite the greater surface litter along roadways, roadside transects were more likely to include exposed rocks (R > ¼ inch in size) than undisturbed rangeland ($F_{1, 144}$=9.56, $p$ =0.002). In contrast, control sites had more woody debris (WD) on the soil surface relative to roadsides ($F_{1, 144}$=7.58, $p = 0.007$), and more exposed soil (S), although the difference in exposed soil was not significant ($p = 0.09$). Lichens were more common in control sites ($F_{1, 144}$= 6.62, $p = 0.01$). Levels of duff (D; decomposed plants that are no longer recognizable) and embedded litter (EL) did not differ between roadsides and undisturbed, control sites. Non-vegetative litter (NL), representing trash and other debris, was greatest along roads ($p = 0.007$).

Foliar cover was divided into cover of introduced and native plants along roadside and control transects, and we detected greater levels of foliar cover of weedy species close to the roadway ($F_{1, 144}$=81.03, $p < 0.0001$.). In addition, the relationship between introduced and native foliar cover was strongly negatively correlated across all control and road transects ($p$ <0.0001), suggesting that greater cover of invasive, weedy species corresponded with lower cover of native species. Total foliar cover was never 100% along any transect and mean foliar cover was 64%.

### 3.1.6 Canopy Gaps

The average number (9.17) of gaps greater than 20 cm in length along road transects was significantly lower than the average number (11.15) of gaps in undisturbed, control sites ($p$ = 0.047), although the total sum of gaps did not vary between treatments ($p = 0.1$). This result likely reflected differences in vegetative structure between roads and nearby, undisturbed rangeland. A comparison of the most common native and non-native species between treatments can demonstrate structural heterogeneity, and roadside vegetation was much more likely to be dominated by crested wheatgrass (AGCR) and cheatgrass (BRTE), while control sites were more commonly dominated by big sagebrush (Fig. 9).

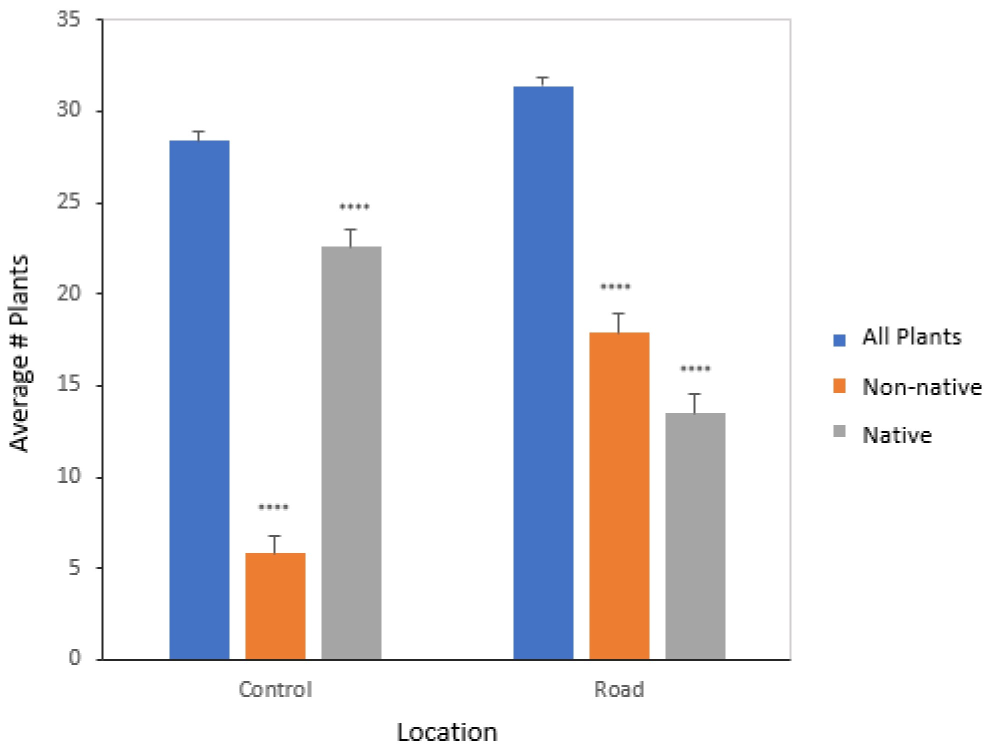


**Figure 5. The average number of plants and the average number of non-native and native plants detected in control and road transects along 12 highways at 73 sites in Wyoming (**** $p < 0.001$, standard error bars represent +1)**

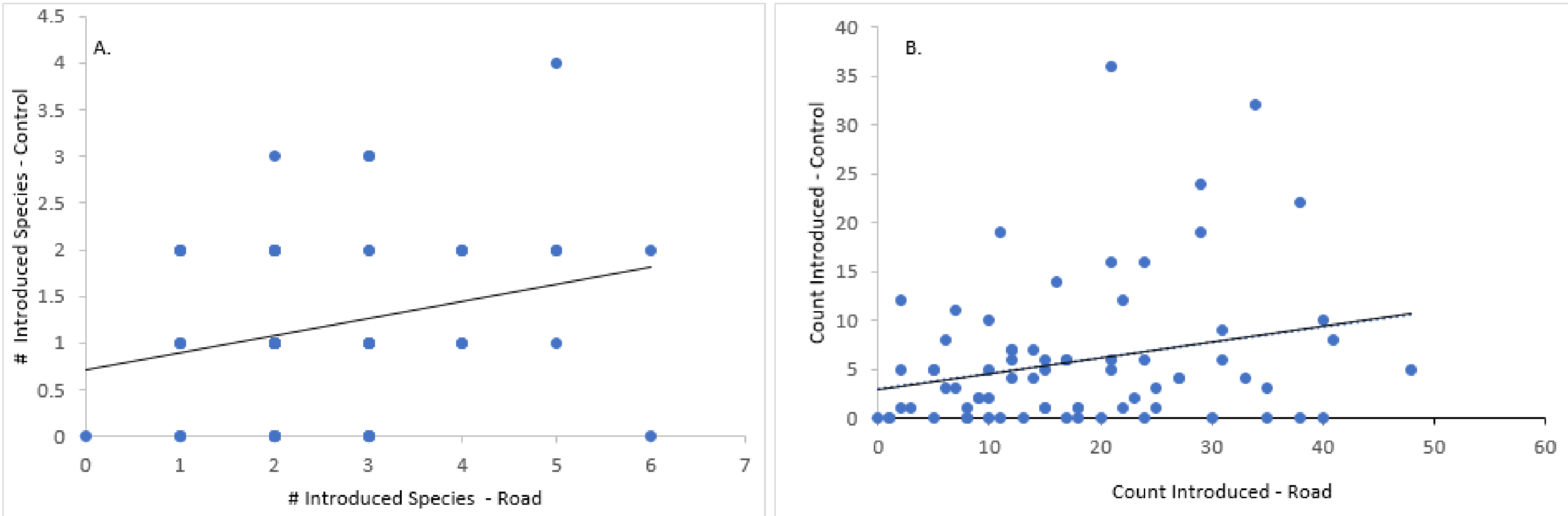


**Figure 6. Comparisons of the number of introduced species (A) along roadside and control transects and the count (or abundance) of introduced plants (B) along roadside and control transects at 73 sites along 12 highways in Wyoming ($p = 0.03$; R-sq =0.06)**

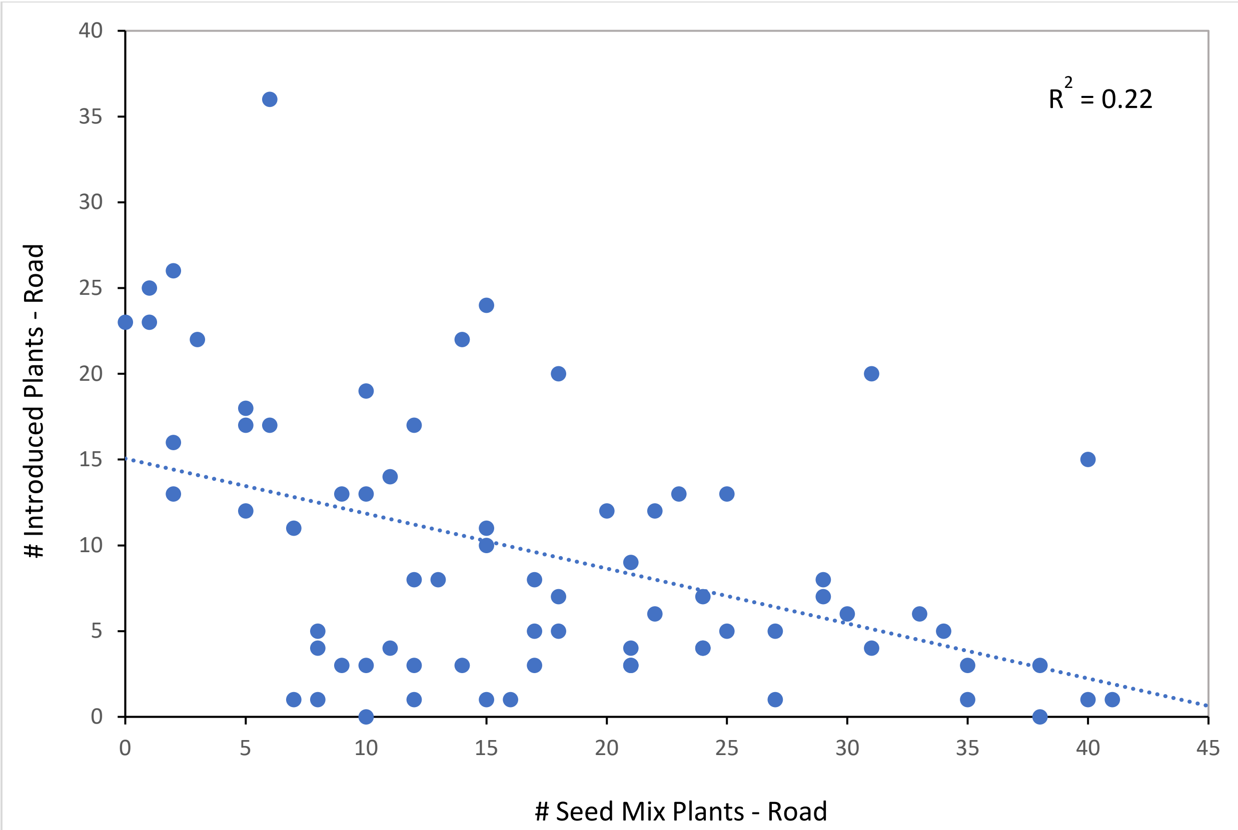


**Figure 7. Relationship ($p < 0.0001$) between the numbers of seed mix plants and the numbers of introduced plants growing along 73 roadside sites in Wyoming where each point represents the number of individual plants of one or more species**

### 3.1.7 Soil Samples

Soil samples were classified into three categories describing the road edge, the average of two samples along the roadside prior to the fence line, and control sites representing the three samples per transect in undisturbed rangeland (Karim and Mallik 2008). Electrical conductivity was significantly higher along the road edge relative to the roadside and control sites ($p < 0.0001$; mean 0.57 vs. 0.36 and 0.42 respectively). The values for sodium and the sodium adsorption ratio, however, were not significantly different ($p = 0.06$ and $p = 0.26$, respectively). Samples along the road edge were significantly higher for potassium concentration relative to the roadside and interior control sites ($p = 0.0052$; mean 0.92 vs. 0.41, 0.39 respectively), but there were no detectable differences in calcium concentration, and magnesium was borderline ($p = 0.05$) with the highest average magnesium concentrations along the road edge. Nitrate nitrogen (NO3- N) concentrations were higher along road edges, but high variability among sites resulted in no significant difference across the sampled categories. Total nitrogen and carbon differed significantly, with a greater concentration of carbon along the road edge ($p > 0.0006$) and a greater concentration of total nitrogen in control sites relative to either the road edge or the roadside ($p = 0.0034$).

Of the four heavy metals, only lead and zinc differed significantly among the categories of road edge, roadside, and controls. Lead was significantly higher in concentration along the road edge relative to the roadside and control sites ($p < 0.0001$; mean 10.48 vs. 7.73, 7.61 respectively), reflecting contamination due to leaded gasoline more than three decades after the transition to unleaded fuel. Zinc was significantly lower in concentration along the road edge relative to the roadside and control sites ($p < 0.007$; mean 28.2 vs. 33.1, 32.9, respectively). There was no significant difference across categories for cadmium and copper. Tests for soil texture did not follow a predictable pattern, with the road edge more closely resembling control sites than the nearby roadside samples. The road edge and control sites were sandier than the two points along the roadside ($p = 0.005$), and the soils along the roadside had a higher percentage of clay ($p = 0.007$) than either the road edge or control sites. This result may reflect soil manipulation during road construction. Overall, soil sampled along Wyoming roads and interior rangeland was classified as either sandy loam, loamy sand, or sandy clay loam.

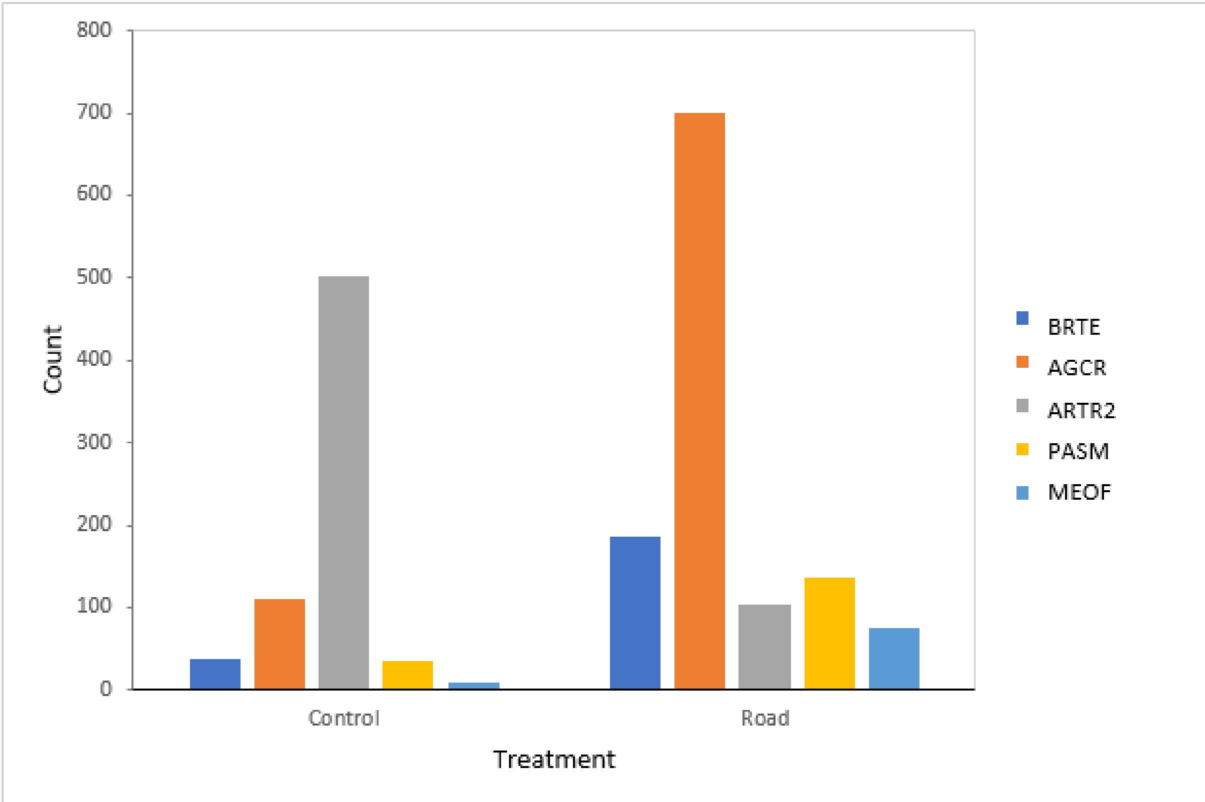


**Figure 8. An illustration of the variation in species counts summed across road and control transects in a study of 73 sites along 12 highways in Wyoming**

### 3.1.8 Discussion

Many factors affect the establishment of seeded species in revegetation programs, including harsh environments and the presence of invasive weeds. One strategy to reestablish a diverse, native plant community has been to increase the number and functional diversity of species included in the seed mix (Pilliod et al. 2017). This strategy is reflected in the growing number of seeded species along Wyoming roadsides, including comparable proportions of grasses and forbs in the list of all unique species planted at 73 roadside sites, as well as several seeded shrubs. However, seed mix species often fail to establish in revegetation programs, and the Great Basin is a well-documented example. One Great Basin study of 88, post-fire revegetation sites seeded with an average of 6 species found that most sites did not show an increase in seeded species cover relative to unseeded, controls (Knutson et al. 2014).

In this study, 36% of seeded species were detected in roadside revegetation surveys, and the eight most planted species had the highest success rate between two- and twenty-years post-seeding.  The 36% may be a conservative estimate as we were unable to distinguish between several species of *Elymus*.  Despite the large number of forbs on the species list, most projects emphasized grasses by including a larger number of grass species relative to forbs and shrubs in mixes applied at each site.  Approximately two-thirds or 64% of seed mix species were not detected in vegetation surveys, and many were forbs that were planted in only one of the 31 projects.  Given the large number of forbs represented by transect data (and the surrounding rangeland), the higher establishment rate of native grasses may be a product of the higher grass application rate rather than the suitability of grasses for roadside reclamation (Dickson and Busby 2009).  However, roadside seed mixes must meet more than one objective including stormwater and erosion control, and roadside safety and management also play a role in seed mix selection (e.g., Eloff and van Niekerk 2005; Mastro et al. 2008).  It is noteworthy that the seed mix species with the greatest success of establishment closely resembled vegetation in nearby, undisturbed sites.  This suggests that matching seed mixes to reference vegetation located near the road reclamation project may improve overall establishment and long-term sustainability of seeded plant communities.

When considering explanations for low rates of seeded species establishment, one possibility is the negative impact of competition, both among seeded species and between seeded species and invasive weeds.  Mangla et al. (2011) studied grassland restoration and found that non-native weeds (cheatgrass and medusahead, *Taeniatherum caput-medusae*) were significantly better competitors than native grasses such as Sandberg bluegrass (*Poa secunda*).  Many similar studies have documented the competitive ability of invasive plants and detrimental impacts of weedy species on native plant establishment (e.g., Svejcar et al. 2017).  Competition is not only one-sided, however, and dominant plant species such as native perennial grasses can also suppress non-native weeds such as cheatgrass (Blank and Morgan 2012; Davies et al. 2014; Clements et al. 2022).  Indeed, suppression of non-native weeds is one goal of roadside reclamation (Steinfeld et al. 2007).

Results of this study found that larger numbers of seeded native plants along roadsides corresponded to significantly reduced foliar cover and abundance of invasive weeds.  This outcome is particularly significant given the positive correlation between levels of roadside weeds and weed abundance in nearby, relatively undisturbed rangelands. While the underlying cause of reduced weed abundance at seeded sites is beyond the scope of this study, roadside seeding outcomes likely impact the invasion of costly, non-native plants in Wyoming landscapes. Thus, while roadside revegetation suffers from mixed success and would benefit from studies to maximize seed mix establishment, evidence supports continued roadside seeding with native species to meet the dual purpose of right-of-way stabilization and weed control, increasing the potential for minimized roadside maintenance and the long-term benefits for environmental health (Weltz et al. 2014).

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## Appendix A.

Key of all species detected in a study of 12 highways and 73 sites representing both roadsides and control transects in central and southern Wyoming. Classifications follow the USDA Plants Database and include the Elymus category to account for seed mix species difficult to distinguish from related species in the genus.

| Symbol | Scientific Name | Status | Life Form |
|---|---|---|---|
| **AGCR** | *Agropyron cristatum* | Introduced | Grass |
| **ALAL3** | *Alyssum alyssoides* | Introduced | Forb |
| **ALDE** | *Alyssum desertorum* | Introduced | Forb |
| **ATPA4** | *Atriplex patula* | Introduced | Forb |
| **BASC5** | *Bassia scoparia* | Introduced | Forb |
| **BRAR5** | *Bromus arvensis* | Introduced | Grass |
| **BRIN2** | *Bromus inermis* | Introduced | Grass |
| **BRTE** | *Bromus tectorum* | Introduced | Grass |
| **CETE5** | *Ceratocephala testiculata* | Introduced | Grass |
| **DESO2** | *Descurainia sophia* | Introduced | Forb |
| **HAGL** | *Halogeton glomeratus* | Introduced | Forb |
| **LASQ** | *Lappula occidentalis* | Introduced | Forb |
| **LEPE2** | *Lepidium perfoliatum* | Introduced | Forb |
| **MAAF** | *Malcolmia africana* | Introduced | Forb |
| **MEOF** | *Melilotus officinalis* | Introduced | Forb |
| **PHPR3** | *Phleum pratense* | Introduced | Grass |
| **POBU** | *Poa bulbosa* | Introduced | Grass |
| **POPR** | *Poa pratensis* | Introduced | Grass |
| **SCLA6** | *Scorzonera laciniata* | Introduced | Forb |
| **SIAL2** | *Sisymbrium altissimum* | Introduced | Forb |
| **TAOF** | *Taraxacum officinale* | Introduced | Forb |

| | | | |
|---|---|---|---|
| **TRDU** | *Tragopogon dubius* | Introduced | Forb |
| **ACHY** | *Achnatherum hymenoides* | Native | Grass |
| **ACMI2** | *Achillea millefolium* | Native | Forb |
| **ALTE** | *Allium textile* | Native | Forb |
| **ANPA4** | *Antennaria parvifolia* | Native | Forb |
| **ARFR4** | *Artemisia frigida* | Native | Shrub |
| **ARLU** | *Artemisia ludoviciana* | Native | Shrub |
| **ARPE6** | *Artemisia pedatifida* | Native | Shrub |
| **ARTR2** | *Artemisia tridentata* | Native | Shrub |
| **ASBI2** | *Astragalus bisulcatus* | Native | Forb |
| **ASFL** | *Astragalus flavus* | Native | Forb |
| **ASFLF** | *Astragalus flexuosus* | Native | Forb |
| **ASGE** | *Astragalus geyeri* | Native | Forb |
| **ASKE** | *Astragalus kentrophyta* | Native | Forb |
| **ASPE5** | *Astragalus pectinatus* | Native | Forb |
| **ATCO** | *Atriplex confertifolia* | Native | Shrub |
| **ATGA** | *Atriplex gardneri* | Native | Shrub |
| **BOER4** | *Bouteloua eriopoda* | Native | Grass |
| **CADO2** | *Carex douglasii* | Native | Graminoid |
| **CADU6** | *Carex duriuscula* | Native | Graminoid |
| **CHBE4** | *Chenopodium berlandieri* | Native | Forb |
| **CHVI8** | *Chrysothamnus viscidiflorus* | Native | Shrub |
| **CRCE** | *Cryptantha celosioides* | Native | Forb |
| **DEPI** | *Descurainia pinnata* | Native | Forb |
| **ELEL5** | *Elymus elymoides* | Native | Grass |
| **ELGL** | *Elymus glaucus* | Native | Grass |

| | | | |
|---|---|---|---|
| **Elymus** | *Elymus lanceolatus, Elymus trachycaulus* | Native | Grass |
| **ERCE2** | *Eriogonum cernuum* | Native | Forb |
| **ARHOH3** | *Arenaria hookeri* | Native | Forb |
| **ERNA10** | *Ericameria nauseosa* | Native | Shrub |
| **ERPA30** | *Ericameria parryi* | Native | Shrub |
| **ERUM** | *Eriogonum umbellatum* | Native | Forb |
| **FEID** | *Festuca idahoensis* | Native | Grass |
| **GRSP** | *Grayia spinosa* | Native | Shrub |
| **GRSQ** | *Grindelia squarrosa* | Native | Forb |
| **GUSA2** | *Gutierrezia sarothrae* | Native | Forb |
| **HAFL2** | *Hackelia floribunda* | Native | Forb |
| **HECO26** | *Hesperostipa comata* | Native | Grass |
| **HENU** | *Helianthus nuttallii* | Native | Forb |
| **HEVI4** | *Heterotheca villosa* | Native | Forb |
| **IVAX** | *Iva axillaris* | Native | Forb |
| **JUARL** | *Juncus arcticus* | Native | Graminoid |
| **JUSA** | *Juncus saximontanus* | Native | Graminoid |
| **KOMA** | *Koeleria macrantha* | Native | Grass |
| **KRLA2** | *Krascheninnikovia lanata* | Native | Shrub |
| **LAOC3** | *Lappula occidentalis* | Native | Forb |
| **LEDE** | *Lepidium densiflorum* | Native | Forb |
| **LILE3** | *Linum lewisii* | Native | Forb |
| **LIPU11** | *Linanthus pungens* | Native | Forb |
| **LOAR5** | *Logfia arvensis* | Native | Forb |
| **LODI** | *Lomatium dissectum* | Native | Forb |
| **LOFO** | *Lomatium foeniculaceum* | Native | Forb |

| | | | |
|---|---|---|---|
| **MONU** | *Monolepis nuttalliana* | Native | Forb |
| **OPPO** | *Opuntia polyacantha* | Native | Shrub |
| **PASE** | *Paronychia sessiliflora* | Native | Forb |
| **PASM** | *Pascopyrum smithii* | Native | Grass |
| **PHAN4** | *Phlox andicola* | Native | Forb |
| **PHHO** | *Phlox hoodii* | Native | Forb |
| **PHLO2** | *Phlox longifolia* | Native | Forb |
| **PLPA2** | *Plantago patagonica* | Native | Forb |
| **POSE** | *Poa secunda* | Native | Grass |
| **PSSP6** | *Pseudoroegneria spicata* | Native | Grass |
| **RICE** | *Ribes cereum* | Native | Shrub |
| **RUSA** | *Rumex salicifolius* | Native | Forb |
| **RUVE2** | *Rumex venosus* | Native | Forb |
| **SAVE** | *Sarcobatus vermiculatus* | Native | Forb |
| **SCLI** | *Schoenocrambe linifolia* | Native | Forb |
| **SPCO** | *Sphaeralcea coccinea* | Native | Forb |
| **STAC** | *Stenotus acaulis* | Native | Forb |
| **SYFA** | *Symphyotrichum falcatum* | Native | Forb |
| **VUOC** | *Vulpia octoflora* | Native | Grass |
| | | | |