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Regional Optimization of Roadside Turfgrass Seed Mixtures Phase 2: Regional Field Trials and Economic Analysis

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16. Abstract (Limit: 250 words)

Our goal was to develop seed mixture recommendations to improve establishment and development of roadside vegetation in Minnesota. We selected 14 research sites across Minnesota and seeded 40 turfgrass mixtures. Turfgrass coverage was assessed at each site twice a year and the weed seed bank was examined. We found that greater seeded turfgrass species richness was important for increasing and stabilizing roadside turfgrass coverage across space. We also found differences in the type and density of the weed seed bank at many sites, but its impact was relatively low on weed coverage over time. We considered soil and weather variables and found three significant seeding clusters for Minnesota consisting of two geographical seeding clusters (north and central/south) and one non-geographical cluster for sites with poor soil quality. Three new mixtures for each cluster were recommended for Minnesota. Implementing these mixtures will reduce soil erosion, improve aesthetics, save local communities' financial resources, and improve the overall environment we occupy. As a complement to the field research, we developed cost prediction models that were incorporated into a detailed enterprise budget tool to calculate the roadside establishment costs that include labor, water, seed, sod, fertilizer, and other factors. This Excel-based tool can be used by local and state officials in determining budgets for roadside installations and which types or combinations of turfgrasses would be most cost effective, while also generating optimal performance.

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Regional Optimization of Roadside Turfgrass Seed Mixtures Phase 2: Regional Field Trials and Economic Analysis

FINAL REPORT

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ALK – alkaligrass
BD – bulk density
BUF – buffalograss
HDF – hard fescue
GLM – generalized linear model
GLMM – generalized linear mixed model
KBG – Kentucky bluegrass
LAT – latitude
LSD – least significant difference
MDOT – Michigan Department of Transportation
MDOT TUF – Fine fescue/perennial ryegrass/weeping alkaligrass/Kentucky bluegrass seed mixture from the Michigan Department of Transportation
MnDOT – Minnesota Department of Transportation
MNST-12 – Fine fescue/Kentucky bluegrass mixture seed or sod
NMDS – non-metric multidimensional scaling
OM – organic matter
PCA – principal component analysis
PIE – probability of an interspecific encounter
PLS – pure live seeds
PRCP – rainfall precipitation
SE – standard error of the estimate
SEC – saturated paste extract electrical conductivity
SLC – slender creeping red fescue
SNOW – snowfall precipitation
SNWD – average snow depth
TF – tall fescue
TMAX – temperature maximum
TMIN – temperature minimum

EXECUTIVE SUMMARY

Establishing persistent vegetation along roadsides is challenging in cold climates. These areas are subject to snowplow damage, winter freezing and ice encasement, excessive heat and drought, application of deicing salt, and little maintenance; they also often contain poor soils. The result is low vegetation cover that leads to more soil erosion and greater vulnerability to weed invasion. In this project, we identify adapted turfgrass mixtures for use in Minnesota that perform well through multiple growing seasons.

All field experiments were conducted at 14 roadside research sites in Minnesota. Each of these sites was located along a two- to four-lane road with different traffic volumes. We collected soil for a weed seed bank analysis that took place in the greenhouse using the soil emergent method. Then, at these same roadsides, a turfgrass mixture experiment was seeded that consisted of 44 treatments composed of both monocultures and mixtures. Each site contained three blocks in a randomized complete block design; seven of the sites were seeded in the fall of 2018 and seven in the fall of 2019. The total coverage was assessed at each site twice a year using the quadrat-grid intersection method.

The first experiment sought to identify the effect of including greater turfgrass species richness in a seed mixture on the coverage over time. We found a significant positive interaction with turfgrass coverage as a function of the number of species and time, suggesting that turfgrass coverage increased through time when more species were included in a mixture. This finding showed that roadsides maintained without regular fertilizer applications and no supplemental irrigation after establishment would benefit from greater species richness in a seed mixture.

In the next experiment, we wanted to characterize the weed seed bank at these different sites and understand if it affects the weed coverage over time in the field plots. We found that there were differences in the seed bank at many sites. A range of more than nine times was found in seedling density (87–791 seedlings gal-1 (23–209 seedlings L-1)) between sites. Differences were also found in observed and estimated species density. Despite the significant differences in the type and density of the seed banks, impact was relatively low on weed coverage over time. Weed coverage was found to be lower when turfgrass coverage was maintained over time.

The Minnesota Department of Transportation (MnDOT) currently recommends turfgrass mixtures that are used statewide without regard to site adaptation. If specific regions or locations with similar conditions in Minnesota, which we refer to as “seeding clusters,” were identified, it could improve the applicability of turfgrass mixture recommendations and likely result in more turfgrass coverage over time. To identify these seeding clusters, we need to consider both soil and weather variables, because their interaction are two important factors influencing many roadside mixture experiments. After collecting soil and weather variables from each site, we perform an agglomerative hierarchical cluster analysis. We validate the results of the clustering by comparing the species composition at sites. Our results suggest an optimal clustering consists of two geographical seeding clusters in Minnesota (north and central/south) and one non-geographical cluster for sites that contain poor soil quality. Poor soil quality sites generally contain more sand, greater bulk density, a higher saturated paste extract electrical conductivity, and lower organic matter. We recommend additional soil testing procedures for practitioners before seeding a site to identify whether it is potentially problematic.

We developed cost prediction models that can be used to estimate costs for future roadside turfgrass establishment projects. We collected construction input quantity and cost data from MnDOT plan sheets of previous projects. Using this data, we first developed a single model that required more than 30 inputs, which turned out to be cumbersome for users. For the final model, we divided the dataset into three subgroups, and developed economic cost prediction models for each subgroup. The new prediction tool required fewer inputs, 16 inputs at most, while maintaining a good level of accuracy. After the models were developed, we programmed the models into Excel and generated a user-friendly cost prediction tool. The prediction tool can predict the total cost for roadside projects. It can also be used to analyze the cost change when certain input quantities change.

From the findings of our cluster analysis, we qualitatively developed three roadside turfgrass seed mixtures for Minnesota. These mixtures were recommended in addition to the currently recommended mixtures. We limited the species recommendations to ones that were tested in this experiment. Seeding mixtures designed for these three clusters in Minnesota will result in improved coverage over time, allowing roadside vegetation to better fulfill its intended functions while saving municipalities financial resources.

CHAPTER 1: INTRODUCTION

1.1 OVERVIEW

This report describes the short and long-term effects of seeding of roadsides with turfgrass, examines whether increasing species richness is effective to improve roadside turfgrass coverage over time, assesses whether the seed bank influences field weed coverage over time, and identifies new roadside seeding clusters accounting for 12 key soil and weather variables that are thought to influence roadside turfgrass coverage. The economics of roadside turfgrass seeding to create optimal tools is also examined. Collectively, this report recommends new principles and mixtures for the State of Minnesota to improve the health of roadside vegetation and save resources for municipalities and local communities.

1.2 JUSTIFICATION

Roadsides comprise a significant quantity of land area in the United States. Estimates indicate 1% of the area of a particular state can comprise roadside vegetation (Forman, 2000). Since roadsides buffer diverse ecosystems and habitats, it is important to establish vegetation that not only reduces erosion but also decreases the spread of invasive plants.

We studied the effects of increasing species richness on turfgrass coverage and stability to identify if findings from the ecological literature extend to managed roadsides. Determining similar beneficial effects in roadside seed mixtures may improve general principles of developing better roadside turfgrass mixtures.

Our second experiment examined seed banks and their effects on weed coverage of roadsides. Understanding the vegetation in the seed bank may provide greater ecological understanding of establishment, as previous research has suggested establishing roadsides with turfgrass mixtures is difficult. A better holistic understanding of establishment could enable practitioners to be more successful and result in a reduction of invasive weeds to surrounding ecosystems.

Improving the applicability of turfgrass mixtures to specific areas or conditions in Minnesota is thought to improve turfgrass establishment and persistence over time. The climate is diverse in Minnesota and a change of turfgrass species and cultivar recommendations for different environments would improve results, since there are currently only statewide recommended seed mixtures by MnDOT. By collecting relevant variables affecting turfgrass coverage we can identify unique seeding clusters.

Seeding and sodding roadsides is expensive, because the area needed to be revegetated can be quite large. Accounting for seed mixtures and establishment practices by accounting for cost allows the ecological principles of improving coverage on roadsides to be balanced with the economic consideration. Developing tools for practitioners to make better decisions on revegetating roadsides will save financial resources for MnDOT, practitioners, and local communities.

Designing and developing new mixtures for Minnesota roadsides based on ecological principles and findings in our study provides additional movement towards roadsides with less erosion since turfgrass mixtures will be establishing and persisting better in areas that they were designed for. This also maintains welcoming communities with vegetation boulevards that survive and thrive.

1.3 TURFGRASS SEED MIXTURES FOR ROADSIDES AND LOW-INPUT ENVIRONMENTS IN COLD CLIMATES

1.3.1 Purpose and benefits of turfgrass for roadsides

Seeding turfgrass along roadsides maintains visibility for drivers, can be relatively cost efficient to establish and manage, reduces erosion, and provides an aesthetically uniform landscape (Boeker, 1970; Duell & Schmit, 1975; Hottenstein, 1969; White & Smithberg, 1972). Mixtures are seeded based on the assumption that species are differentially adapted to environmental conditions. The intended function of a roadside generally allows for higher weedy tolerances and less uniformity than a park or home lawn.

The use of species mixtures, compared to monocultures, has been shown to have multiple benefits, including more coverage of the seeded species (Tyser et al., 1998), less weed coverage (McKernan et al., 2001), reduced disease frequency and severity (Dunn et al., 2002; Xiang et al., 2019), and extended green color (Johnson, 2003). Turfgrass mixtures also have the potential to fulfill more functions (Hector & Bagchi, 2007); for instance, turfgrass species may have different rooting depth and heterogeneity (Brown et al., 2010) and a mixture designed with this function can reduce erosion (Simon & Collison, 2002). Burt et al. (2020) suggested that planting a mixture of 27 species, including turfgrasses, could potentially support up to 520 insect species. Xie et al. (2020) found a mixture of strong creeping red fescue (*Festuca rubra* L. ssp. *rubra* Gaudin) and Kentucky bluegrass (*Poa pratensis* L.) compared to Kentucky bluegrass alone resulted in greater soil microbial diversity, different soil microbial communities, and fewer turfgrass pathogens.

1.3.2 General factors affecting the results of turfgrass mixture experiments

Species included for roadsides should be tolerant of higher salinity (Biesboer & Jacobson, 1994), poor and ill-timed management (White & Bailey, 1969), no supplemental irrigation, and little to no fertilizer inputs. Even though a roadside is a low-input environment, it does not imply that roadside vegetation should receive no routine maintenance (Hottenstein, 1969); rather, species should seldom be included for roadsides that are known to only thrive in higher-input conditions.

When selecting turfgrasses to tolerate less inputs, it is important to recognize that individual species and cultivars have a range of adaptations to differences in climate, soil, and management factors. Turfgrass species have different tolerances to fertility levels (Beard, 1973; Hunt & Dunn, 1993), timeliness of germination and robustness of establishment (Bunderson, 2007; Dunn et al., 2002), salt tolerance (Friell et al., 2013), heat tolerance (Breuillin‐Sessoms & Watkins, 2020; Xu et al., 2018), ice tolerance (Guðleifsson, 2010; Watkins et al., 2018), drought tolerance or avoidance (Qian et al., 1997), and other abiotic and biotic stresses; therefore, an appropriate mixture needs to be designed to tolerate and thrive in any combination of these stresses.

The intensity, duration, and frequency of maintenance can have an impact on turfgrass mixture experiments (Watschke & Schmidt, 1992). For instance, some turfgrass species, such as bentgrass (*Agrostis* L. spp.), and weeds, such as smooth crabgrass (*Digitaria ischaemum* (Schreb)) and large crabgrass (*Digitaria sanguinalis* (L.) Scop.), are known to be better adapted to a lower height of cut (Davis, 1958; Dernoeden et al., 1998; Juska & Hanson, 1959). White and Smithberg (1972) found that the interval between mowing times is more significant than the mower type and that smooth bromegrass (*Bromis inermis* Leyss.) is more abundant on roadsides in Minnesota where mowing is less frequent. Hunt and Dunn (1993) found greater disease incidence at a lower mowing height in mixtures of cool-season grasses.

Soil and edaphic conditions can influence the results of turfgrass mixture experiments. At three Michigan roadsides sites, Martin and Kaufman (1970) found Kentucky bluegrass dominated a loamy clay site while strong creeping red fescue was primarily the only seeded grass remaining on the sandy site. The inclusion of tall fescue, redtop bentgrass (*Agrostis gigantea* Roth), creeping bentgrass (*Agrostis stolonifera* L.), orchardgrass (*Dactylis glomerata* L.), and smooth bromegrass provided no significant benefit at the three research sites tested. In Minnesota, White and Smithberg (1972) found when seeding mixtures of Kentucky bluegrass, redtop bentgrass, white clover (*Trifolium repens* L.), and perennial ryegrass (*Lolium perenne* L.) on roadsides that redtop bentgrass dominated sections with higher soil moisture, and Kentucky bluegrass and smooth bromegrass dominated the drier areas. Similar results with redtop bentgrass were reported by Foote et al. (1978). Duell and Schmit (1975) found turf-type Kentucky bluegrass and tall fescue performed poorly on high-sand and low-nutrient soils and there were general difficulties establishing grass at a site containing 96% sand. Despite slow establishment, hard fescue (*Festuca brevipila* Tracey) ‘C-26’ had consistently one of the best ratings at the end of the 5-year experiment; the authors’ final recommendations for New Jersey roadsides included an even ratio of strong creeping red fescue, common-type Kentucky bluegrass, then either Chewings fescue (*Festuca rubra* L. ssp. *commutata* Gaudin; syn. *Festuca rubra* L. ssp. *fallax* (Thuill.) Nyman) or hard fescue. Foote et al. (1978) tested different mixtures at four roadside research sites and found it especially difficult to maintain turfgrass coverage on excessively sandy sites but found that sand dropseed (*Sporobolus cryptandrus* (Torr.) Gray), smooth bromegrass, Russian wildrye (*Psathyrostachys juncea* (Fisch.) Nevski), and timothy grass (*Phleum pratense* L.) could be more suitable for these conditions. Henslin (1982) found sheep (*Festuca ovina* L.) and hard fescue dominated at an exceptionally dry site near Rice, MN. Henslin (1982) also presented some evidence showing superior varieties at one site had dissimilar performance at sites with different soil types but similar climates; a final recommendation included strong creeping red fescue, Canada bluegrass (*Poa compressa* L.), hard fescue, and sheep fescue for sandy well-drained roadside areas.

1.3.3 Limitations of many turfgrass mixture experiments

Comparing turfgrass mixture experiments on roadsides and other low-maintenance areas is difficult and there are many limitations. Coverage is evaluated for a few years or less (Engelhardt & Ratliff, 2019; Friell et al., 2012, 2015; Henensal et al., 1980), and in that period, the number, type, order, and duration of stresses may be different or lacking, and therefore the analysis may result in poor recommendations. An experiment that collected longer-term data would provide future advantages or disadvantages of some species and mixtures (Damgaard & Weiner, 2017). For example, tall fescue (Friell et al., 2015) and perennial ryegrass (Friell et al., 2012) are susceptible to winter injury on roadsides in Minnesota, but if they are evaluated for a year or less, the results may find them to be superior simply based on a low-severity winter.

It is also difficult to compare turfgrass mixture experiments because many design and mix species by weight. Consider the fact that a common turfgrass mixture, such as 90% tall fescue to 10% Kentucky bluegrass by weight is nearly a 1:1 seed ratio. Weight is then generally more arbitrary. Furthermore, there are differences in seed lot purity, germination rate, and differences in seed size between species; cultivar within a species; and seed lots within a single cultivar (Christians et al., 1979). Mixing species by pure live seed or a "field-viable seed" ratio has been recommended before (Brede & Duich, 1984a), since it contains more information than just weight. This allows for better comparison, but there are still differences in environmental conditions and maintenance procedures between experiments, and differences in seeding rate.

1.3.4 Results of turfgrass species and mixture experiments

Testing of turfgrass species usually occurs in monoculture trials with the aim of identifying species and cultivar adaptation. After six years of evaluating coverage on West Virginia roadsides, Blaser (1964) found redtop bentgrass, strong creeping red fescue, and perennial ryegrass had poor coverage. In a low-maintenance experiment in the upper Midwest, Diesburg et al. (1997) found tall fescue and sheep fescue generally performed the best. Buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.) performed adequately in southern Illinois and in Ohio, and colonial bentgrass performed well at a few sites with lower fertility. One limitation of Diesburg et al. (1997) was that there were significant differences in soil quality between sites, which was confounded with the relative regional adaptation. In the northcentral United States, Watkins et al. (2011) found that hard fescue then tall fescue both performed well in a two-year low-input turfgrass study. On the contrary, tall fescue's roadside performance in this region has been shown to be more limited (Friell et al., 2012, 2015; Watkins et al., 2019). This is likely due to prolonged ice encasement (Guðleifsson, 2010).

Testing of less-utilized species has occurred. In Manitoba, Mintenko et al. (2002) reported that blue grama (*Bouteloua gracilis* (Willd.) Lag.), a warm-season native species and prairie junegrass (*Koeleria macrantha* (Ledeb.) Schult.), a cool-season native species, showed consistent green color for the duration of a low-maintenance turfgrass experiment. On roadsides in Minnesota, prairie junegrass had poor establishment after one year (Friell et al., 2012). On roadsides in New England, prairie junegrass was initially not the best, but after two years maintained a steady coverage of 45%, whereas the rest of the species contained less than 25% coverage (Brown et al., 2010). Weeping alkaligrass (*Puccinellia distans* (Jacq.) Parl.) usually results in poor coverage in low-maintenance experiments (McKernan et al., 2001), but occasionally has good coverage along salted freeways when commonly tested turfgrass species are limited (Biesboer et al., 1998; Friell et al., 2012; Watkins et al., 2019).

Many turfgrass mixture experiments have occurred in combinations with two of either Kentucky bluegrass, tall fescue, or perennial ryegrass. Dunn et al. (2002) found in some instances, mixtures of Kentucky bluegrass and tall fescue performed better than a monoculture alone, due to greater disease resistance. Blaser (1964) found the inclusion of 'Kentucky 31' tall fescue and Kentucky bluegrass enhanced long-term coverage in a roadside mixture experiment. In a non-roadside mixture experiment in Minnesota, Miller et al. (2013) found that a blend of tall fescue performed better than a mixture of fine fescues or a mixture of Kentucky bluegrass and tall fescue, and a blend of Kentucky bluegrass cultivars performed the poorest. Brede and Duich (1984a) found that the best performing perennial ryegrass and Kentucky bluegrass mixtures resulted in greater leaf area index, seedling density, ground coverage, and improved spring green-up compared to monocultures.

Mixtures of fine fescue species and Kentucky bluegrass have been previously recommended, likely due to similar competitiveness and therefore good complementarity. Juska and Hanson (1959) seeded 50 different turfgrass mixtures and found that for four years, 'Merion' Kentucky bluegrass monoculture was the best entry, but in the fifth year it significantly declined due to disease. When 'Merion' contained 25%, by weight strong creeping red fescue, then overall plot quality was stable during the disease pressure. Yuan et al. (2014) tested mixtures of Kentucky bluegrass, strong creeping red fescue, and alkaligrass and recommended a mixture of 32% Kentucky bluegrass to 68% strong creeping red fescue, by pure live seed weight. Kentucky bluegrass generally is more competitive under greater nitrogen fertility than fine fescue (*Festuca* L. spp.) species (Juska et al., 1955).

Examples of three or more species in turfgrass mixtures are more limited in the literature. In Missouri, Hunt and Dunn (1993) found mixtures consisting of tall fescue, perennial ryegrass, and Kentucky bluegrass had fewer weeds than a monoculture plot of tall fescue over the duration of a five year experiment; plots were maintained at a low height of cut (16 and 22 mm), and the abundance of tall fescue declined from 51 to 11% in a mixture with perennial ryegrass that was initially seeded at a rate of 8:1 by weight, respectively. In that same period, a mixture of tall fescue and Kentucky bluegrass remained stable. Larsen et al. (2004) found that a 3-way mixture of slender creeping red fescue (*Festuca rubra* L. ssp. *littoralis* (G. Mey.) Auquier), perennial ryegrass, and Kentucky bluegrass, which contained close to half of the viable seeds, that in less than a year, 3-30% of the stand contained Kentucky bluegrass. In Maryland, Dernoeden et al. (1998) found mixing tall fescue and strong creeping red fescue resulted in the best turfgrass quality in the fall for three years when mowed at 6.5 cm and no overall benefit was found in any seed mixture with different mowing treatments.

Multi-species mixtures have also been tested or are currently recommended on roadsides. Friell et al. (2015) found all species except tall fescue improved survival; additionally, they showed some evidence for poor complementarity between mixtures of alkaligrass and slender creeping red fescue and that may limit their use together in mixtures. The authors' final recommendation was limited to the tested constituent proportions, and they recommended the top three species consisting of hard fescue (40%), sheep fescue (40%), and slender creeping red fescue (20%). The current recommended mixture 25-151 (conventional turfgrass) by the Minnesota Department of Transportation (MnDOT), has been recommended in a similar ratio since at least the mid to early 1990s, and it currently contains a mixture by weight of perennial ryegrass (17%), strong creeping red fescue (8%) and a triple blend of Kentucky bluegrass (totaling 75%) (MnDOT, 2014). Perennial ryegrass has been found to disappear rapidly on a roadside in cold climates and so its coverage is likely temporary (Friell et al., 2012; Watkins et al., 2019).

1.3.5 Mixing cool and warm-season turfgrasses

The mixtures discussed above only included cool-season species. Mixing cool- (C_3) and warm-season (C_4) turfgrasses may be useful in some turfgrass management situations as the benefits of both types could be attained resulting in improved seasonal coverage, color, and greater stability to a variety of abiotic and biotic stresses. Roadsides in Minnesota are anecdotally known to contain disproportionately warmer and drier areas than surrounding vegetation, and so cold tolerant warm-season grasses have the potential to perform well in these areas in mid-summer. Weeping alkaligrass has been tested and recommended with native warm-season turfgrasses in Minnesota (Stenlund & Jacobson, 1994), likely since its coverage can behave like an annual (Biesboer et al., 1998), supplying adequate coverage in spring before warm-season turfgrasses begin seasonal growth. Despite the mixed results of mixing cool- and warm-season turfgrasses, there is still potential that a mixture of both could persist. The type of coverage would likely oscillate in abundance with fluctuations in temperature, precipitation, and their interaction, and this may provide long-term benefits for roadside vegetation.

1.3.6 Designing turfgrass mixtures

The design of a turfgrass mixture and most seed mixtures can often be viewed as an art. There may be multiple appropriate ways to mix the type, number, ratio, and rate of species, but there usually are many incorrect ways. Proper design of a turfgrass mixture considers many aspects. An appropriately designed turfgrass mixture would be tolerant to or avoidant of many abiotic and biotic stresses and poor management practices that often occur along roadsides. An effective mixture would also be able to withstand unique and dynamic future stresses considering the climate, soil conditions, and disturbance or management factors, and the timing of seeding relative to the respective growing year. After these considerations, then the type of species can be selected, the number of species, number of cultivars for each species, appropriate ratios of these species, and the seeding rate.

1.4 IDENTIFYING THE HETEROGENEITY OF A SEEDING AREA

A large area or region contains more variation in climate, soil, disturbance, and management factors. Therefore, an important consideration is identifying if a mixture should be designed for a specific site (Kirmer et al., 2012; MacDonagh & Hallyn, 2010) or for a broader region. Turfgrass mixtures for roadsides have been recommended for different moisture regimes (Boeker, 1970; MnDOT, 2014). Testing has also occurred for differences in elevation (Hopkinson et al., 2018) and region (Engelhardt & Ratliff, 2019) which both relate to the climate and soil characteristics. Species and cultivar survival has also been tested with different soil amendments (Brown & Gorres, 2011). The heterogeneity within a region or site may be large or small depending on the conditions and pursuing these questions provides a beneficial beginning when designing a turfgrass mixture.

1.5 SEEDING TIMING

The timing of seeding will modify how a mixture is designed. We know there are optimal periods to seed cool-season turfgrasses (Braun et al., 2021; Minnesota Department of Highways, 1962; Watkins & Trappe, 2017). Seeding timing is important because weed pressure cycles throughout the growing year in Minnesota. Natural weed pressure is lower in the fall, since warm-season annuals have largely concluded their life cycle, but soil temperatures are still relatively high, and this allows for sufficient turfgrass establishment with less weed pressure. When seeding cool-season mixtures in suboptimal timing, previous recommendations have included perennial ryegrass (Henensal et al., 1980) since it establishes quickly acting as a temporary cover crop reducing the abundance of weeds; however, perennial ryegrass modifies the overall competitiveness of the mixture (Engel & Trout, 1980) which could result in shorter-term coverage of that mixture. Other options could consist of applying a preemergent herbicide before seeding, sodding, or seeding a warm-season turfgrass and allowing it to establish and grow for one growing year, then seeding into the thatch from winter kill in the following spring (White & Smithberg, 1972). Appropriate seeding timing needs to be considered to balance the short- and long-term coverage of seeded material and to improve establishment potential.

1.6 SELECTING THE TYPE OF SPECIES

The type of species being selected for an area is an important factor after identifying characteristics of the planting area and timing of seeding. Watschke and Schmidt (1992) reported that when beginning to develop a turfgrass landscape it is important to begin with the most adapted species for the climate, environmental stresses, intended function, and maintenance level. Doing this will also result in one of the most important cultural control of weeds (Busey, 2003).

Mixing other adapted cool season species from other genera, warm-season grasses, and species from other functional groups may provide added benefit over space and time than a group of species behaving similarly. Engelhardt and Ratliff (2019) found differences in regional coverage of species and recommended two warm-season grasses at the central location, since those species established well and resisted invasion of summer weeds, but at the eastern location there was not any good performing seed mixtures, which the authors attributed to excessive weed invasion of crabgrass and foxtail (*Setaria* spp.), along with low plant available soil moisture.

1.7 SELECTING AN APPROPRIATE NUMBER OF SPECIES

More species that are included in a mixture usually results in benefits in both non-roadside (Dunn et al., 2002; Johnson, 2003; McKernan et al., 2001; Tyser et al., 1998; Xiang et al., 2019), and roadside environments. Biesboer et al. (1998) found that a fall seeded mixture of warm-season natives, cool-season natives, and cool-season introduced species, when seeded along a roadside in Cambridge, Minnesota had better cover after two years compared to either a warm-season or a cool-season nonnative mixture alone. Additional roadside research in Minnesota by Henslin (1982), found that mixtures usually performed better if the top monoculture was included in a seed treatment; this illustrates one benefit of the insurance effect (Yachi & Loreau, 1999). Additionally, the testing of some wheatgrass species (*Triticeae*) shows they may have relatively poor coverage by themselves, but when seeded with Kentucky bluegrass in a low-maintenance environment, they can add to improving the coverage and density of turfgrass mixtures (Robins & Bushman, 2020).

1.8 CULTIVAR SELECTION AND NUMBER

The selection, type, and number of cultivars in a mixture is important, since adapted cultivars can also result in fewer weed problems (Busey, 2003). Some roadside experiments have attempted to identify cultivars that are the most suitable for roadsides and differences have been found based on the age of the cultivar of some species (Friell & Watkins, 2020). There have been experiments attempting to identify the most adapted roadside cultivars in controlled environments (Biesboer & Jacobson, 1994; Breuillin-Sessoms & Watkins, 2020; Friell et al., 2013; Watkins et al., 2018) and field experiments (Brown & Gorres, 2011; Friell et al., 2012; Watkins et al., 2019). Results of these studies show differences within individual species; however, Brown and Gorres (2011) found that cultivar differences may not necessarily matter to the long-term performance at a roadside site if it contains poor soil conditions. There also may be differences in mixability of cultivars within different species. This is rarely tested, but variation likely exists, since it has been shown in wheat (Knott & Mundt, 1990; Lopez & Mundt, 2000) and soybean (Gizlice et al., 1989). Barot et al. (2017) provides a review of cultivar mixability. Overall, the type and characteristics of turfgrass cultivars that allow for greater mixability and improved performance on roadsides should be further explored.

1.9 SELECTING SPECIES RATIOS

Even if the appropriate type of species, number, and most adapted cultivars were selected, the designated ratios of different species in a mixture is highly important to success. A poorly designed mixture could result in excessive dominance by one species. An appropriate ratio of species in a mixture is one that allows for adequate short-term coverage whilst not overwhelming the potential of species that establish slower.

One of the most common mistakes in the design of cool-season turfgrass mixtures is including species that establish too quickly and robustly in high proportions, thereby dominating the stand and not allowing other species to establish. Perennial ryegrass included at 10% or greater by weight and less depending on which species it was seeded with, greatly interferes with the establishment of other species (Dunn et al., 2002; Henensal et al., 1980). Brede and Duich (1984a) found that an optimum mixture of Kentucky bluegrass to perennial ryegrass ranged from 70-95% field viable seeds of Kentucky bluegrass. This allowed for good establishment and low perennial ryegrass clumping. However, perennial ryegrass' inhibition on other species in a mixture cannot be overstated, since it can result in reduced plant sizes of Kentucky bluegrass, strong creeping red fescue, and colonial bentgrass when seeded together (Engel & Trout, 1980). Great care must take place to limit its seed ratio in mixtures to not reduce the competitive ability of these longer-term grasses.

1.10 SEEDING RATE

Another aspect to designing a turfgrass mixture is the seeding rate. Patton et al. (2004) found greater coverage with higher seeding rates in two warm-season grasses at first, but after 42 and 70 d of seeding bemudagrass (*Cynodon dactylon* var. *dactylon* (L.) Pers.) and zoysiagrass the coverage was the same for all seeding rates, although the authors anecdotally observed greater density of higher seeding rates and lower biomass of individual tillers, similar to Lush (1990). Christians et al. (1979) found that the same weight of seeding smaller-seeded cultivars of Kentucky bluegrass compared to larger-seeded cultivars resulted in no difference in coverage after 6 growing months. Stenlund and Jacobson (1994) found no differences when doubling the seeding rate of one mixture along a roadside. L. Li et al. (2016) found that buffalograss seeding rate also had no impact on coverage. Overall, there are few differences in establishment with different seeding rate but testing different seeding rates along with different mixtures would likely benefit from additional testing.

1.11 CONCLUSION

An appropriately designed mixture is one that can provide adequate short and long-term erosion control, result in a reasonably uniform and pleasing landscape, be cost efficient, and to serve drivers in safer movement and transportation. More research on turfgrass mixtures and evaluating these experiments over longer durations will allow for improved recommendations. This will save municipalities resources and improve the overall sustainability of seeding and maintaining roadsides. This report contains the identification and characterization of the seed bank at 14 roadside research sites, the effects of increasing species richness of turfgrass seed mixtures, recommended turfgrass seeding clusters for the state of Minnesota, economics of roadside revegetation, and final overall recommendations including new seed mixtures for the state of Minnesota.

CHAPTER 2: THE EFFECTS OF INCREASING TURFGRASS SPECIES RICHNESS FOR MINNESOTA ROADSIDES

2.1 INTRODUCTION

Roadsides are often planted with turfgrass seed mixtures. Designing these mixtures to withstand salting, ice encasement, temperature and moisture extremes, snowplow damage, and poor maintenance is difficult. Mixtures for roadsides and other low-maintenance areas have been recommended with a range in diversity. There is a tendency to only add species to a mixture if there is a visible and measurable benefit (Blaser, 1964); this may be a flawed approach in that it fails to consider the limitations of the study area relative to a region. Therefore, we sought to explore the benefits of seeded turfgrass species richness in a roadside mixture experiment planted at sites throughout Minnesota in two different years. Our objective was to determine if greater turfgrass species richness affects turfgrass, weed, and bare soil coverage. We expected to find a significant benefit of the addition of each additional species over time resulting in more seeded turfgrass coverage, fewer weeds, and less bare soil coverage.

2.2 MATERIALS AND METHODS

2.2.1 Research sites

Fourteen research sites were selected across the state of Minnesota (Figure 2.1) to represent a broad range of climatic conditions found in the state. Each research site was immediately adjacent to a curb along a two to four-lane road in full sun conditions, except for Chatfield and Edina, which were partially shaded. Differences in traffic volumes and the amount and type of winter salting were not controlled for. Additionally, there were differences in slope and aspect within and between some sites.

2.2.2 Species selection

Species selected for this experiment included five cool-season grasses and one warm-season grass (buffalograss) (Table 2.1). The cool-season species were selected based on previous testing and performance in Minnesota (Friell et al., 2012, 2015) Buffalograss was selected based on its adaptability to well-drained, sunny roadsides, since it is an abundant species in the shortgrass prairie, a warmer and drier climate than Minnesota (Johnson et al., 2001). Cultivars were selected based on their persistence of coverage in a field experiment covering multiple states (Watkins et al., 2019), and/or in a greenhouse experiment assessing the performance of different cultivars to salinity, ice, and heat, which are considered the three most limiting abiotic factors for turfgrass along roadsides (Breuillin-Sessoms & Watkins, 2020; Watkins et al., 2018). Additionally, three check mixtures that are currently seeded along roadsides in Minnesota (25-131, 25-151, MNST-12) (MnDOT, 2014) and one in Michigan (MDOT TUF) were included (Table 2.2).

2.2.3 Germination testing

To be consistent with the definition of a mixture experiment, the total number of seeds was held constant for each treatment (Cornell, 1973). The total number of pure live seeds (PLS) was determined through germination testing (AOSA, 2016) and purity. Germination for each species was tested with four repetitions of 100 seeds that were kept moist with a 2% solution of KNO_3. An exception to these rules was buffalograss, which is planted as burs that contain more than one caryopsis. Germination for buffalograss was defined as the total sum of radicals that emerged from each seed, and germination did not account for potentially dormant or hard seeds. Each plot was seeded at 13 PLS in^2 (2 PLS cm^{-2}). The weight of each species was determined by counting, weighing, and averaging four repetitions of 1000 seeds. Purity was considered 99% in PLS calculations, unless noted from the seed supplier, except for the four check mixtures for fall 2018 research sites where purity was incorrectly specified as 99%.

2.2.4 Mixture design

Extreme vertices simplex design from the *Xvert* function in the mixexp package in R (R Core Team, 2021) was used to design mixtures (Lawson & Willden, 2016). Buffalograss was limited to 5% total pure live seeds due to a lower seeding rate because of its stoloniferous growth. The *Fillv* function from the mixexp package was used to add interior points to the mixture design. To reduce the total number of treatments to fit the physical space available we implemented a design optimization algorithm from the *optFederov* function in the AlgDesign package (Wheeler, 2019), and this resulted in an uneven number of treatment combinations with each number of species. This resulted in 36 total seed treatments (six turfgrass species represented by a single cultivar in monocultures, pairwise interactions, some three-way mixtures, and a single six-way mixture) in addition to the 4 check mixtures that are shown in Table 2.3.

2.2.5 Experimental design

Forty treatments were seeded at seven sites in each of fall 2018 and fall 2019. Each site was a randomized complete block design consisting of 40 treatments with three blocks for a total of 120 plots. Individual plots were 25 ft^2 (2.3 m^2) and adjacent to the curb and perpendicular stretching 5 ft (1.5 m) from the curb. At some sites, there were obstructions such as road signs, hydrants, driveways, and walk-ways and so sections of 5–33 ft (1.5–10 m) spaces sometimes existed between plots; otherwise, there was no buffer between plots. At sites seeded in 2018, 'Navigator II' strong creeping red fescue was seeded in buffer areas and the border behind the plot area. The border behind the plot area was parallel to the road a width of 3.3 ft (1 m), as space allowed, except for Grand Rapids, which was not seeded in the border area. For research sites seeded in 2019, ‘SeaMist’ slender creeping red fescue was seeded in the border areas.

2.2.6 Soil sampling and testing

Prior to site establishment, 45–60 soil cores per site were collected in August and September by using a small soil core in a pattern that zig-zagged the plot width. Cores were sampled to a depth of 4–6 in (10–15 cm) at each research site and composited by block. These were analyzed for available phosphorus using the Bray and/or Olsen method, K, organic matter (OM) content, pH, saturated paste extract electrical conductivity, soil texture, and four heavy metals (Fe, Mn, Zn, and Cu) because some are associated with greater weed abundances (Bae et al., 2015). The results of the soil test by research site are shown in Table 2.4. Fine and total soil bulk density was tested at each site between June–Aug. 2020 using the excavation approach and determining the volume with the water method (Page-Dumroese et al., 1999). After removing bulk density soil, it was brought back to the laboratory and weighed, and then sieved using a two mm screen, and lastly oven dried at 105 ° C until final weight was stable (Page-Dumroese et al., 1999). Bulk density results are shown in Table 2.5. Other physical characteristics calculated were the gravimetric and volumetric fragment content, gravimetric water content, and soil porosity. Additionally, potential plant available water was calculated for each block at all research sites (Saxton et al., 1986).

2.2.7 Research site establishment

Seven sites were initiated in the fall of 2018 and seven in the fall of 2019. Each site was sprayed 1–2 wks prior to tillage and then immediately before tillage with a 5% solution of glyphosate (Cornerstone Plus) (WinField Solutions LLC, St. Paul, MN) to kill existing vegetation. Sites were then tilled with a rotary tiller to 4–6 in (10–15 cm) depth and raked to smooth the surface and remove excess debris. A photo of the experimental setup before seeding is shown in Figure 2.2. All plots were seeded by hand and then gently raked in two directions if not overly saturated, in which case no raking occurred (this did not appear to affect plot establishment). A Futerra F4 netless blanket (Profile Products LLC., Buffalo Grove, IL) was then laid over plots and adhered to the surface using 4 in (10.2 cm) length biostaples (Ecoturf Midwest Inc., Elmhurst, IL). There was some movement of seeds between plots in the second block of Chatfield, where the slope is relatively steep compared to other sites and where a nearby natural spring resulted in greater soil moisture for a portion of that block. A single application of fertilizer was applied to each research site after seeding at a rate of 24.2, 19.1 and 44.3 lb/ac (27.2, 21.4, and 49.7 kg ha^{-1}) of N-P-K (10-18-22) (EC Grow Prolinks, EC Grow, Eau Claire, WI).

2.2.8 Irrigation

Research sites were irrigated with a modular drip irrigation system (Watkins et al., 2020) for 15–49 d after seeding. There were four drip lines each spaced 18 in (46 cm) apart and the spacing was held between drip lines by securing it with sod staples every 20 ft (6 m). Plots received 0.16–0.24 in (0.4–0.6 cm) of water twice per day (at 8:00 and 13:00). The total number of irrigating days varied between sites due to the date of seeding and if a significant freeze was expected. The Brainerd site was not irrigated by the drip system but instead by a water truck, a common practice for establishing roadside turfgrasses. The water truck irrigated Brainerd five instances of approximately 0.31 in (0.8 cm) at each application. No irrigation was applied after the removal of the modular drip irrigation system. Photos of the irrigation setup are shown in Figure 2.3-2.4.

2.2.9 Plot maintenance

Research sites received no chemical weed control for the duration of the study, except for the Worthington site which was once inadvertently sprayed with a broadleaf herbicide in plots 1–34 by a lawn care company. No fertilizer was applied after the initial starter application. Most sites were mowed and maintained by our research team, but several were mown by respective municipalities. The mode height of cut for all plots was 3.25 in (8.3 cm) usually every 14-21 d (Table 2.6). In a few instances, municipalities accidentally mowed plots shorter at a height between 1.5–2.5 in (3.8-6.4 cm). Plots were regularly leaf blown to remove excessive dead plant matter and debris off the plot area, and in the spring some soil debris was occasionally raked or removed by hand from the plots.

2.2.10 Data collection

The plant species and total ground cover was collected at each site over two growing seasons. The total cover of all research sites was quantified twice per year, once in the fall (Sep.-Nov.) and once in the spring (April-Jun.) using the quadrat-grid intersection method (Wilson, 2011). The grid contained an area of 12.5 ft^2 (1.16 m^2) with 30 intersections spaced regularly and data was collected on two areas of each plot, for a total of 60 data points per plot. At the first two sampling periods (fall and spring) coverage was classified as either turfgrass, bare soil, or weeds. Additionally, at the first fall sampling period at all sites, and at one instance the following spring at Grand Rapids, a picture was taken with the grid laying over the plot and coverage at intersections were classified later using the image. Debris was occasionally identified at the point of the intersection from the images, and this was not counted as debris, but instead as missing data, so each instance lowered the total number of intersections (or data points) for a particular plot. All subsequent sampling, starting approximately one year after seeding was classified into one of the five species that were seeded (Table 2.1); hard fescue and slender creeping red fescue are difficult to distinguish in the field so were grouped into the same classification of "fine fescue". Other classifications consisted of perennial ryegrass, which was included in three of the check mixtures;

white clover, a common roadside broadleaf at many sites; sedge (*Cyperaceae*); rush (*Juncaceae*); other grass; other broadleaf; bare soil; or a tree sapling. The dates that each site was seeded and sampled is shown in Table 2.7. A photo of the sampling grid for data collection is shown in Figure 2.5.

2.2.11 Statistics

All analysis and data preparation were conducted using the open-source software R (R Core Team, 2021). A generalized linear mixed model (GLMM) was conducted in the lme4 package (Bates et al., 2014) using the *glmer* function with family set to binomial. The three primary response variables were seeded turfgrass, weed, and bare soil coverage (%). The fixed effect predictor variables were the season of sampling (fall or spring), time defined as the order of vegetation sampling (i.e., 1=first-time sampling vegetation, 2=second-time sampling vegetation, etc.), number of species seeded in the treatment (1-6), and the interaction between time and number of species. Research site was included as a random effect. Model selection was guided by minimizing the AIC score for generalized linear mixed models

Spatial stability of both turfgrass and weed cover was calculated by the mean divided by the standard deviation (Lehman & Tilman, 2000). The average coverage and standard deviation were calculated from all research sites and blocks composited resulting in a total of 360 observations (40 treatments · five sampling times for sites seeded in 2018 + 40 treatments · four sampling times for sites seeded in 2019). The subsequent dataset contains average coverage and standard deviation for 40 treatments (Table 2.3) at different sampling times for sites seeded in either 2018 or 2019.

Two linear models using the *lm* function in R were developed with the spatial stability of turfgrass and weed cover as response variables. The response variables were natural log transformed based on the results of a box-cox analysis. A small value of 0.1 was added to weed spatial stability prior to transformation to reduce undefined values; this was not an issue for turfgrass spatial stability values. Linear model estimates are shown exponentiated to simplify model interpretation. The predictor variables included in the model were the seeding year (2018 or 2019), season of sampling (fall or spring), time (1-5), and number of species (1-6). The linear model selection was guided by maximizing the R^2. An effort was made in all model selection to reduce complexity and only include the most relevant main and interaction effects. Statistical assumptions were analyzed graphically, and some minor deviations were present on the lower and upper portions of the normality of error assumption on the linear models. All results containing the number of species relate to the number of seeded species within a treatment and not necessarily the number of observed species.

2.3 RESULTS

2.3.1 Turfgrass coverage

Differences in turfgrass coverage by site and number of species seeded in each treatment are shown in Figure 2.6. The GLMM analysis for turfgrass coverage showed a significant positive interaction between time, defined as the order of sampling instances, and number of species (Est=0.08, S.E.=0.02, P<0.001) (Table 2.8). The predicted effects of the interaction between time and number of species are shown in Figure 2.7 with the effect of additional species resulting in greater turfgrass coverage as time increases. Average turfgrass coverage, standard deviation, and spatial stability for each treatment is shown in Figure 2.8-9. A linear model showed that a one-unit change in the number of species resulted in 1.05-1.12 times increase in turfgrass spatial stability. ($F_{4,355}$=8.34, P<0.001) (Table 3.9). Each additional time increment was found to result in 1.00-1.07 times increase in turfgrass spatial stability (P=0.04) (Table 2.9).

2.3.2 Weed coverage

No significant interaction effect existed for number of species and time on weed cover in the GLMM analysis (P=0.08) (Table 2.8). When the time by number of species interaction effect was not included in the model for weed coverage, the main effect of the number of species was highly significant (Est=-0.55, S.E.=0.05, P<0.001) and negatively associated with weed coverage. When sampling total coverage in the spring, there was significantly less weed coverage (Est=-1.03, P<0.001). A one-unit increase in time resulted in significantly more logged odds of weed coverage (Est=0.88, P<0.001). Average weed coverage, standard deviation, and spatial stability for each treatment is shown in Figure 2.10-11. Weed spatial stability resulted in 0.92-1.00 times decrease ($F_{4,355}$=79.8, P=0.03) with the increase of each additional turfgrass species (Table 2.10). Each additional time increment was found to result in 1.34-1.44 times increase in weed spatial stability (P<0.001) (Table 2.10).

2.3.3 Bare soil coverage

No significant interaction effect existed between number of species and time affecting bare soil coverage in the GLMM analysis (P=0.37) (Table 2.8), although there was a significant effect of the increase in each additional turfgrass species resulting in lower coverage of bare ground (Est=-0.14, P=0.02). When sampling total coverage in the spring, there was significantly more bare soil coverage (Est=0.67, P<0.001). A one-unit increase in time resulted in significantly less bare soil coverage (Est=-1.14, P<0.001) (Table 2.8).

2.4 DISCUSSION

The importance of roadside turfgrass species diversity for maintaining persistent cover has been understated previously. We found greater turfgrass species richness increased turfgrass coverage over time, resulted in less weed coverage, and less bare soil. Additionally, more species in a mixture had greater turfgrass spatial stability. These findings support the development of roadside seed mixtures containing more species for transportation agencies. In some studies, there has been a tendency to simplify roadside mixtures by including few species (Blaser, 1964; Boeker, 1970; Friell et al., 2015), but many of these experiments were conducted at one or two research sites, and so results often showed a few adequate performers. Seed mixtures have been simplified for different planting environments such as by drainage classes (Boeker, 1970), but this should not reduce mixture diversity to a few species, even if drainage class and proximity to the road are similar, as our experiment showed there are benefits of increasing species richness.

Previous testing along roadsides has found different performance of individual species and cultivars (Friell et al., 2012; Friell & Watkins, 2020), and these differences are likely based on climate, edaphic conditions of a site, and disturbances. Species asynchrony and response diversity (Sasaki et al., 2019) of adapted species and cultivars to roadsides should be included in the design of roadside mixtures; this can be achieved by including more diversity at the species level, and then including additional cultivars within a species (Barot et al., 2017).

Our findings show that seeding greater species richness will allow greater turfgrass cover, but it is also important to design mixtures with appropriate proportions, otherwise the benefits of greater richness would be reduced. Previous research in both roadside and non-roadside settings have found that including perennial ryegrass greater than or equal to 10% by weight can reduce the quality of other species in a mixture, because perennial ryegrass establishes very quickly (Dunn et al., 2002; Henensal et al., 1980). We observed that tall fescue and slender creeping red fescue, two of the quickest establishing species included in our study, can reduce the establishment of hard fescue, Kentucky bluegrass, and buffalograss, which are all slower establishing species. On roadsides in Minnesota, Friell et al. (2015) found that the coverage of tall fescue was lower than the original proportion in its seed mixture, so reducing the proportion of this species in mixtures may not only allow for better establishment of other species, but could be more cost-efficient. When hard fescue, a slower establishing species, was a top performer at a site, we found that its monoculture performance was sometimes better than the high diversity mixtures. The long-term advantage of hard fescue has been noted before on roadsides in Minnesota (Friell et al., 2012), and it has been underutilized in historical roadside turfgrass mixtures recommended for the state (MnDOT, 2014).

Establishing and maintaining vegetation along roadsides is difficult and seed mixtures have historically been designed with varying levels of diversity, but often with too little diversity. Roadsides also contain differences in environmental factors such as the climate, soil physical and chemical characteristics, disturbance, and management. Our findings show that when planting across numerous research sites there is a measurable increase in turfgrass coverage with the addition of each species over time. A potential limitation of this study is that data collection for sites seeded in 2018 occurred for two-years, and one and a half years for plots seeded in 2019, and we know the abundance of some species are more rapidly changing at some sites. Overall, we recommend including greater species in seed mixtures for roadsides to provide more coverage that is also more spatially stable. This will result in roadside vegetation that continues to reduce soil erosion, provides a short-stature and aesthetically uniform landscape, and maintains safe pathways for drivers.

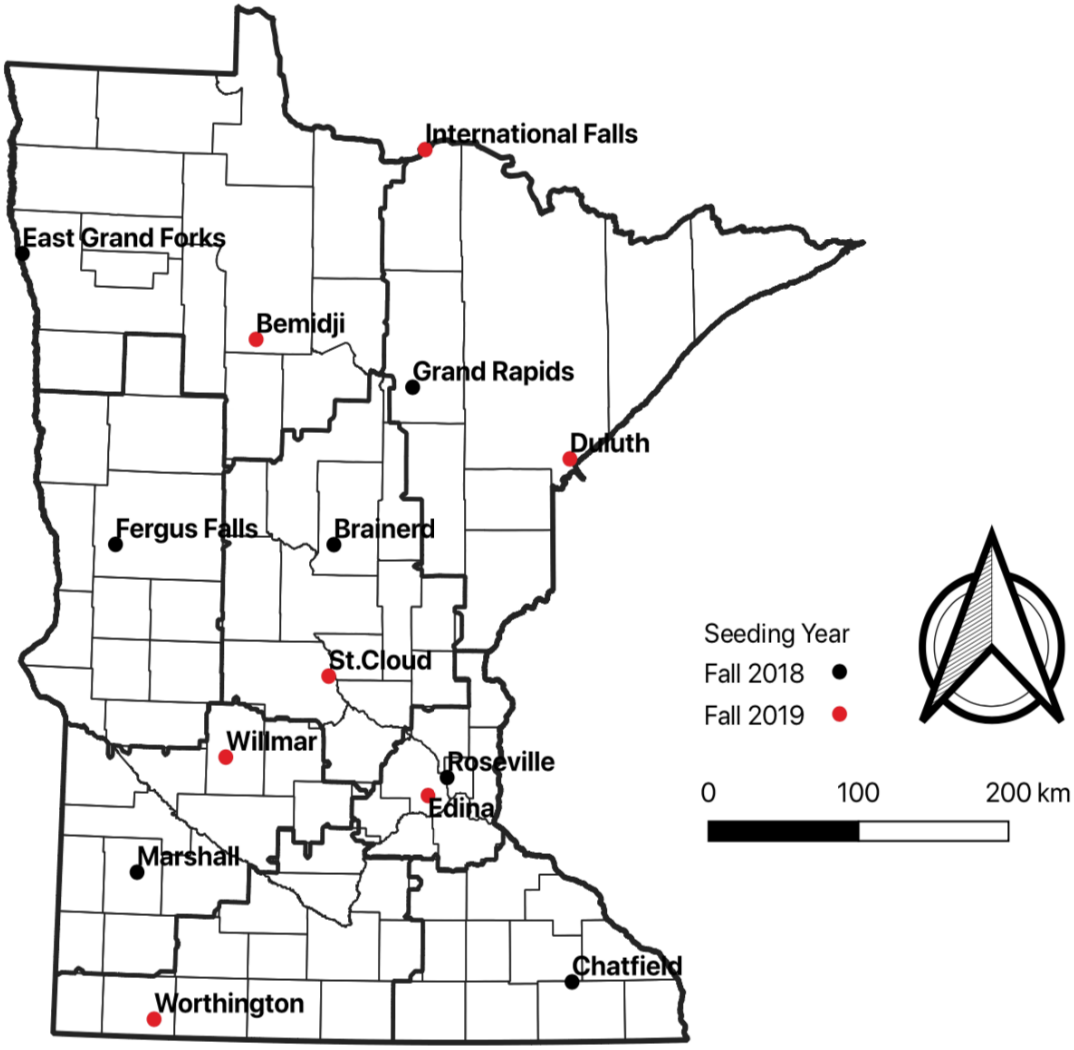

Figure 2.1 Map showing fourteen research sites that were seeded in the state of Minnesota. The dark thick boundaries represent the eight MnDOT regions, and the thinner boundaries distinguish the counties.

Figure 2.2 Dr. John Trappe preparing soil bed before seeding. This photo was taken at the Marshall, MN roadside research site on Sep. 17, 2018.

Figure 2.3 Photo showing irrigation drip lines aiding turfgrass establishment. This photo was taken at the Chatfield, MN roadside research site on Oct. 4, 2018, approximately 16 d after seeding.

Figure 2.4 Sampling grid used for assessing coverage. This photo was taken at the Worthington, MN roadside research site on Oct. 25, 2019, approximately 51 d after seeding.

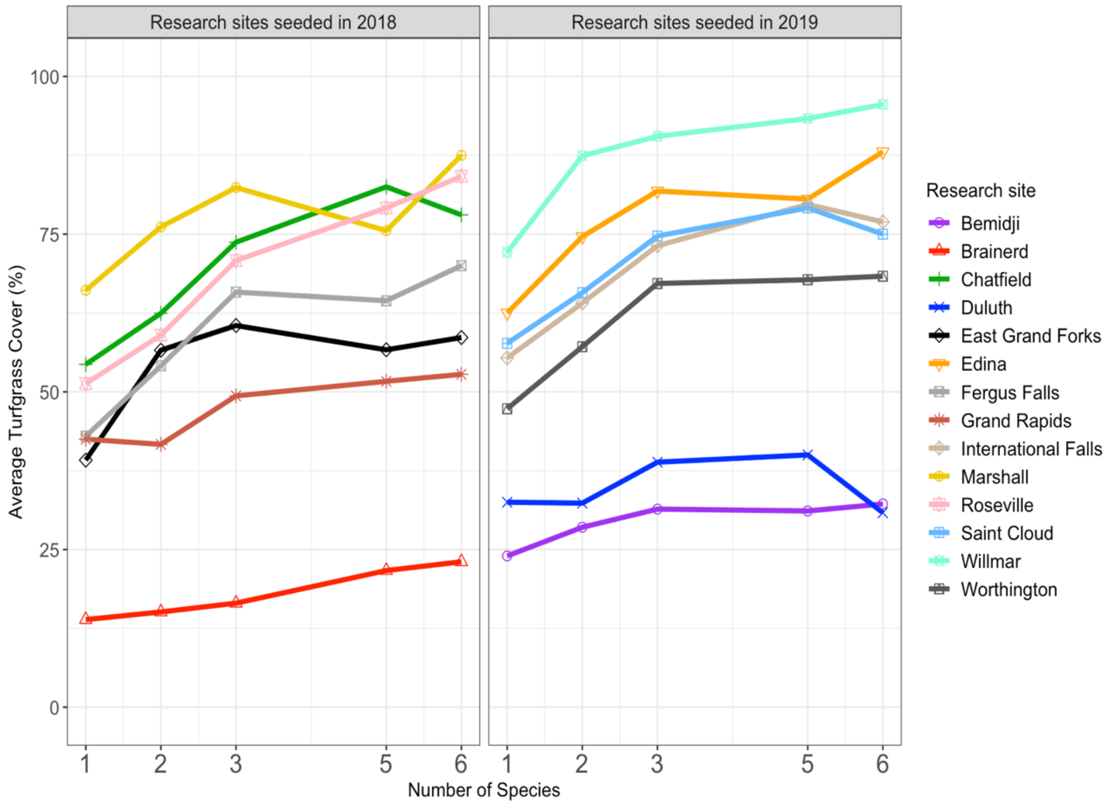

Figure 2.5 The average turfgrass coverage as a function of the turfgrass species richness for 14 research sites. This figure shows coverage when sampling occurred in the fall of 2020.

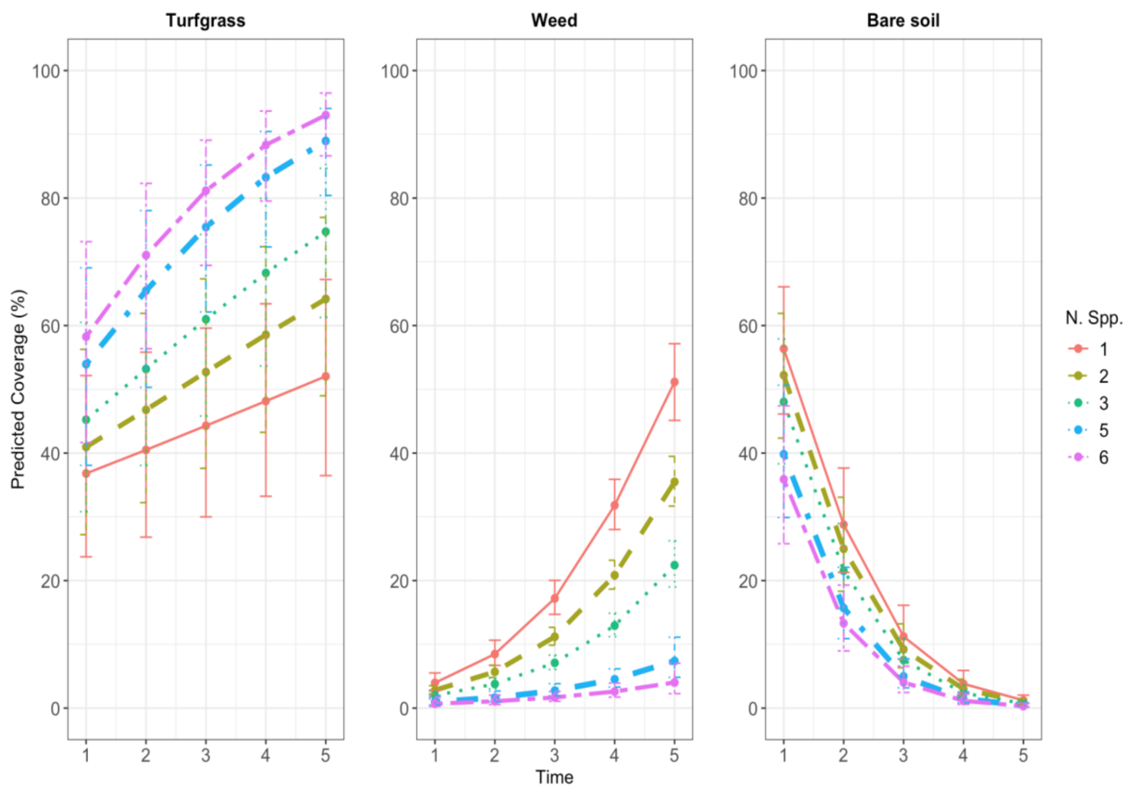

Figure 2.6 GLMM predictions of time and the number of species for the plot area covered by turfgrass, weed, or bare soil. Odd time increments were sampled in the fall and even in the spring. Error bars show the 95% confidence interval. N. Spp. is the number of species included in the seed treatment at the time of seeding. The fifth sampling time contains data only from sites seeded in 2018.

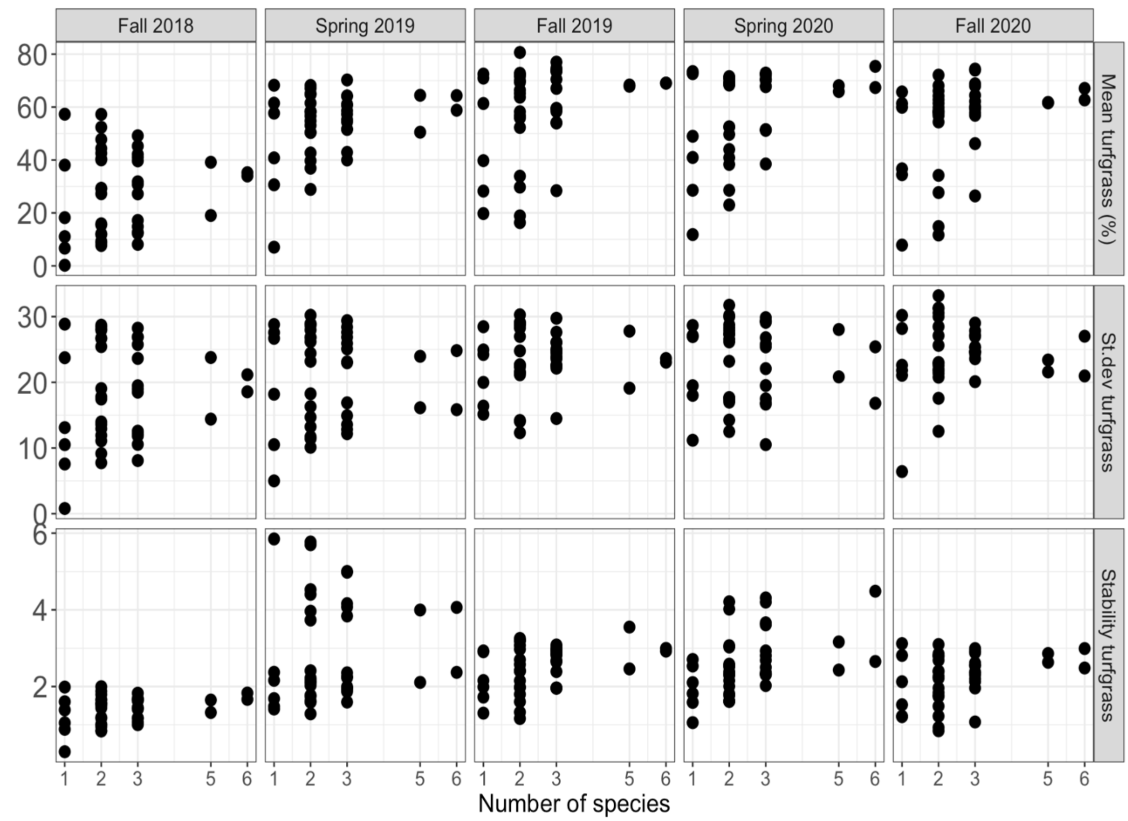

Figure 2.7 Mean, standard deviation, and spatial stability (mean/standard deviation) of turfgrass coverage for each seed treatment for sites seeded in 2018. The addition of alkaligrass in a seed mixture resulted in significantly lower standard deviation in spring 2019, since that was the only species that performed adequately at one site (see open space in the center of the plot). St. dev = standard deviation. Vegetation sampling season and year are shown facetted in the columns.

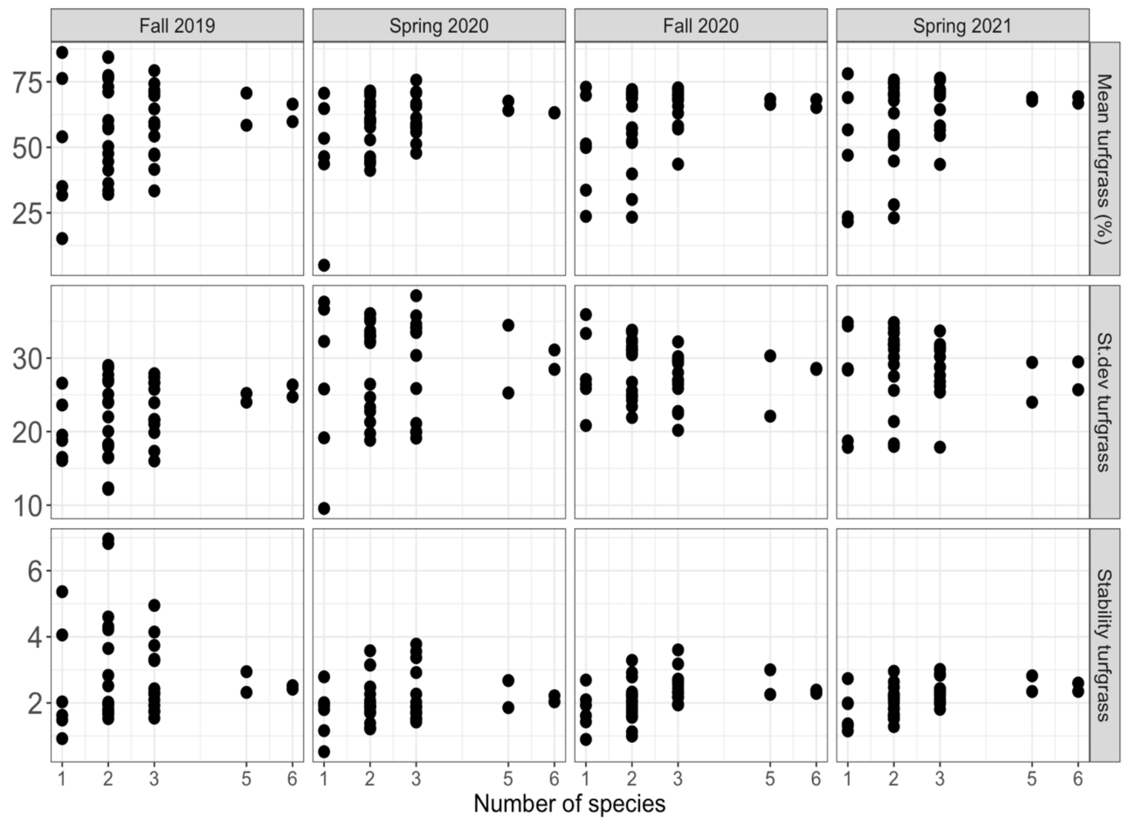

Figure 2.8 Mean, standard deviation, and spatial stability (mean/standard deviation) of turfgrass coverage for each seed treatment for sites seeded in 2019. St. dev = standard deviation. Vegetation sampling season and year are shown facetted in the columns.

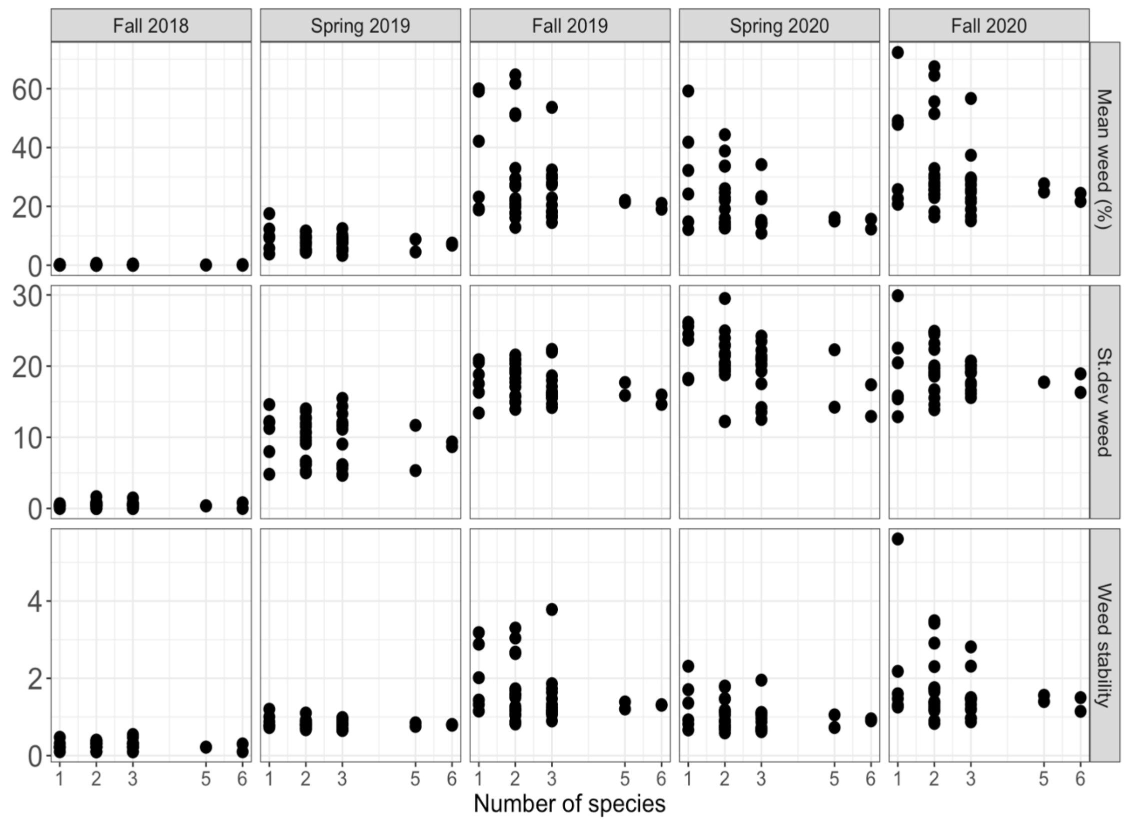

Figure 2.9 Mean, standard deviation, and spatial stability (mean/standard deviation) of weed coverage for each seed treatment for sites seeded in 2018. St. dev = standard deviation. Vegetation sampling season and year are shown facetted in the columns. Undefined stability values changed to 0.1.

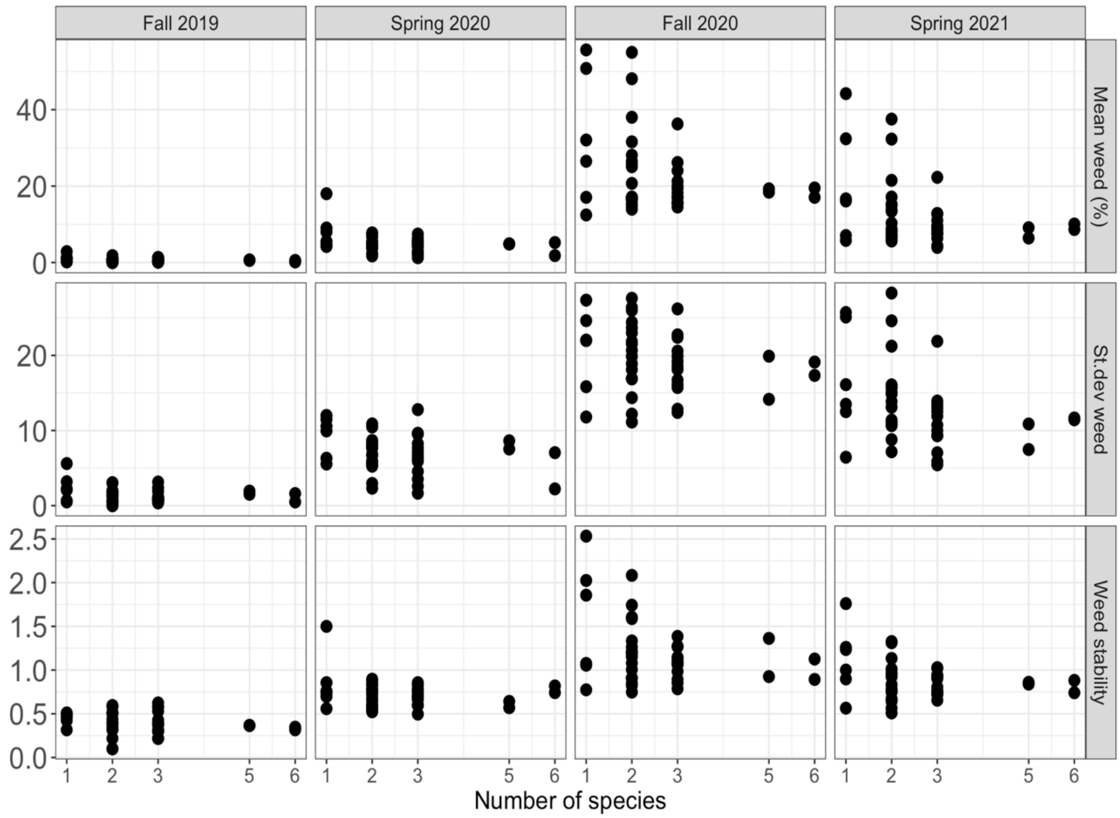

Figure 2.10 Mean, standard deviation, and spatial stability (mean/standard deviation) of weed coverage for each seed treatment for sites seeded in 2019. St. dev = standard deviation. Vegetation sampling season and year are shown facetted in the columns. Undefined stability values changed to 0.1.

Table 2.1 Species and cultivars chosen for this experiment. This list does not include additional species and cultivars that were included with check mixtures.

Common name	**Scientific name**	**Cultivar**
Buffalograss	*Buchloe dactyloides* (Nutt.) Engelm.	Sundancer
Hard fescue	*Festuca brevipila* Tracey	Gladiator
Kentucky bluegrass	*Poa pratensis* L.	Tirem
Slender creeping red fescue	*Festuca rubra* L. ssp. *littoralis* (G. Mey.) Auquier	SeaMist
Tall fescue	*Schedonorus arundinaceus* (Schreb.) Dumort.	Saltillo
Weeping alkaligrass	*Puccinellia distans* (Jacq.) Parl.	Sea Salt

Table 2.2 Species components of seed mixtures for roadsides that were included in the study. The Michigan check mixture is MDOT TUF while other mixtures are recommended by MnDOT.

DOT check mixture name[a]	Seed lot number	Species scientific name	Species common name	Cultivar	Weight (%)[b]	Approx. seed ratio of mixture (%)[c]
MDOT TUF	L152-18-459	*Festuca rubra* L. ssp. *rubra* Gaudin	Strong creeping red fescue	Epic	38.32	32.05
		Festuca brevipila Tracey	Hard fescue	Reliant IV	19.91	16.03
		Lolium perenne L.	Perennial ryegrass	Palmer III	19.02	5.95
		Puccinellia distans (Jacq.) Parl.	Weeping alkaligrass	Salty	9.99	16.30
		Poa pratensis L.	Kentucky bluegrass	Arc	9.92	29.68
25-131	18225A	*Festuca rubra* L. ssp. *rubra* Gaudin	Strong creeping red fescue	Boreal	29.09	21.79
		Festuca rubra L. ssp. *commutata* Gaudin	Chewings fescue	Fairmont	20.00	12.18
		Poa pratensis L.	Kentucky bluegrass	Blue Angel	16.36	43.83
		Festuca brevipila Tracey	Hard fescue	Jetty	13.64	9.83
		Festuca ovina L.	Sheep fescue	Blue Ray	11.37	9.69
		Lolium perenne L.	Perennial ryegrass	Royal Green	9.54	2.67

DOT check mixture name[a]	Seed lot number	Species scientific name	Species common name	Cultivar	Weight (%)[b]	Approx. seed ratio of mixture (%)[c]
25-151	18218A	*Poa pratensis* L.	Kentucky bluegrass	Blue Angel	25.00	31.64
		Poa pratensis L.	Kentucky bluegrass	Park	25.00	31.64
		Poa pratensis L.	Kentucky bluegrass	Merit	25.00	31.64
		Lolium perenne L.	Perennial ryegrass	Shining Star	17.00	2.25
		Festuca rubra L. ssp. *rubra* Gaudin	Strong creeping red fescue	Boreal	8.00	2.83
MNST-12 (2018)	18238B	*Festuca rubra* L. ssp. *rubra* Gaudin	Strong creeping red fescue	Cardinal	19.91	13.78
		Festuca rubra L. ssp. *commutata* Gaudin	Chewings fescue	Radar	19.62	11.04
		Festuca brevipila Tracey	Hard fescue	Jetty	19.75	13.16
		Poa pratensis L.	Kentucky bluegrass	Blue Note	19.60	48.53
		Festuca rubra L. ssp. *littoralis* (G. Mey.) Auquier	Slender creeping red fescue	Seabreeze GT	19.49	13.49

DOT check mixture name[a]	Seed lot number	Species scientific name	Species common name	Cultivar	Weight (%)[b]	Approx. seed ratio of mixture (%)[c]
MNST-12 (2019)	19142B	*Festuca rubra* L. ssp. *commutata* Gaudin	Chewings fescue	Radar	19.96	11.09
		Festuca rubra L. ssp. *littoralis* (G. Mey.) Auquier	Slender creeping red fescue	Shoreline	19.95	13.64
		Poa pratensis L.	Kentucky bluegrass	Diva	19.94	48.76
		Festuca brevipila Tracey	Hard fescue	Beacon	19.93	13.11
		Festuca rubra L. ssp. *commutata* Gaudin	Strong creeping red fescue	Epic	19.61	13.40

[a] Different MNST-12 seed lots were used in different planting years incorporating similar species ratios but only similarity in a single cultivar ('Radar').
[b] Proportion of seed weight in each mixture.
[c] Estimated proportion of the number of seeds in each mixture based on number of seeds per weight.

Table 2.3 The proportion of pure live seed ratios for each species in each of the 40 treatments. MDOT TUF is the Michigan check mixture and 25-131, 25-151, and MNST-12 are recommended by MnDOT.

Treatment	Buffalograss	Tall fescue	Slender creeping red fescue	Kentucky bluegrass	Weeping alkaligrass	Hard fescue
1	100					
2		100				
3			100			
4				100		
5					100	
6						100
7	5	95				
8	5		95			
9	5			95		
10	5				95	
11	5					95
12				50		50
13				50	50	
14			50			50
15			50		50	
16			50	50		
17		50				50

Treatment	Buffalograss	Tall fescue	Slender creeping red fescue	Kentucky bluegrass	Weeping alkaligrass	Hard fescue
18		50			50	
19		50		50		
20		50	50			
21	2.5				97.5	
22	5				47.5	47.5
23	5			47.5		47.5
24	5			47.5	47.5	
25	5		47.5			47.5
26	5		47.5		47.5	
27	2.5	97.5				
28	5	47.5				47.5
29	5	47.5			47.5	
30	5	47.5		47.5		
31	5	47.5	47.5			
32	2.5		48.75	48.75		
33					50	50
34	2.5	47.5				50
35	2.5				47.5	50

Treatment	Buffalograss	Tall fescue	Slender creeping red fescue	Kentucky bluegrass	Weeping alkaligrass	Hard fescue
36	2.5	19.5	19.5	19.5	19.5	19.5
37	MNST-12					
38	25-131					
39	25-151					
40	MDOT TUF					

Table 2.4 Average soil chemical properties for each research site. Greater differences exist between than within a site. Bray P and Olsen P is the available phosphorus in the soil. Bray is reliable when the pH is less than 7.4 and Olsen when it is greater than 7.4. Soil testing was analyzed by the University of Minnesota soil testing laboratory using standard methods.

Research site	Bray P[b]	Olsen P[b]	K[b]	OM	pH	Sat. elect. conductivity (mmhos cm^{-1})[a]	Sand (%)	Silt (%)	Clay (%)	Soil texture[c]	Fe[ab]	Mn[ab]	Zn[ab]	Cu[ab]
Bemidji	38.33	NA	82.00	2.07	7.30	1.07	69.57	10.42	20.01	SCL	19.20	5.44	2.84	0.34
Brainerd	28.67	9.00	78.33	3.10	7.40	0.73	71.23	7.07	21.67	SCL	58.46	4.67	43.29	14.35
Chatfield	25.67	12.00	133.00	2.70	7.50	0.77	52.50	15.87	31.70	SCL	22.99	8.17	1.43	0.38
Duluth	10.00	4.67	56.00	2.60	7.50	1.63	55.01	22.91	22.07	SCL	57.07	6.22	3.74	4.70
E. G. Forks	NA	10.33	239.67	4.97	7.87	0.63	3.93	48.60	47.53	Silty clay	10.14	6.51	1.71	1.40
Edina	26.00	NA	69.67	5.80	7.20	1.43	49.20	25.40	25.40	SCL	40.99	4.69	6.74	1.11
Fergus Falls	15.67	7.33	230.67	5.10	7.90	0.97	50.40	19.63	30.03	SCL	13.09	4.54	6.17	1.15
G. Rapids	38.33	10.67	59.33	1.83	7.43	0.80	60.00	18.33	21.70	SCL	43.00	7.12	2.95	1.03
Int. Falls	4.67	4.00	129.33	6.63	7.53	1.10	41.20	22.10	36.70	Clay loam	40.00	2.03	3.49	1.19
Marshall	8.67	11.00	203.33	4.00	7.77	0.47	34.40	23.50	42.07	Clay	20.25	7.62	3.41	1.19
Roseville	14.50	6.17	74.33	5.13	7.88	0.63	61.67	13.37	25.00	SCL	31.38	3.89	12.82	2.59
Saint Cloud	46.67	NA	142.33	2.70	6.87	1.40	58.31	15.42	26.26	SCL	64.36	8.37	2.42	0.53
Willmar	3.00	NA	183.00	3.43	7.47	1.53	42.49	26.26	31.26	Clay loam	17.73	4.11	5.97	1.02
Worthington	21.00	NA	170.00	5.03	7.30	0.83	16.26	39.58	44.16	Clay	29.06	7.51	2.88	1.01

[a] Saturated paste extract electrical conductivity, Fe, Mn, Zn, and Cu analysis from sites seeded in the fall of 2018 came from additional soil samples collected in summer 2020.
[b] Units of mg kg^{-1}.
[c] SCL = sandy clay loam.

Table 2.5 Fine and total bulk density from each zone (Curb, Mid, Far) within a research site.

	Bulk density (g cm^{-3})							
	Fine				Total (Coarse)			
Research site	Curb[a]	Mid[b]	Far[c]	Avg.	Curb[a]	Mid[b]	Far[c]	Avg.
Bemidji	1.36	1.39	1.39	1.38	1.41	1.43	1.47	1.43
Brainerd	1.47	1.27	1.29	1.34	1.51	1.35	1.34	1.40
Chatfield	1.24	1.19	1.23	1.22	1.29	1.24	1.30	1.28
Duluth	1.28	1.22	1.44	1.31	1.64	1.44	1.74	1.61
E. G. Forks	1.09	1.11	1.14	1.11	1.13	1.13	1.16	1.14
Edina	1.42	1.17	1.26	1.28	1.50	1.22	1.33	1.35
Fergus Falls	1.20	1.20	1.16	1.19	1.29	1.31	1.23	1.28
Grand Rapids	1.49	1.56	1.70	1.58	1.62	1.71	1.81	1.71
Int. Falls	1.07	0.82	0.96	0.95	1.18	0.92	1.05	1.05
Marshall	1.13	1.08	1.08	1.10	1.18	1.17	1.19	1.18
Roseville	1.29	1.18	1.21	1.23	1.32	1.23	1.27	1.27
Saint Cloud	1.30	1.37	1.41	1.36	1.38	1.42	1.48	1.43
Willmar	1.26	1.23	1.38	1.29	1.32	1.31	1.46	1.36
Worthington	1.01	1.08	1.06	1.05	1.06	1.16	1.11	1.11
Average	1.26	1.21	1.26	1.24	1.35	1.29	1.35	1.33

[a] Core sampled immediately adjacent to the curb.
[b] Core sampled 0.8 m away from the curb in the center of the plot.
[c] Core sampled 1.5 m away from the curb on the inside edge of the plot.

Table 2.6 Mowing and other maintenance details at each research sites. We found it difficult to control mowing height and frequency even with preventative measures at some sites.

Research site	Growing year	Mode mowing height (in)	Mode mowing height (cm)	Total number of mows	Average mowing interval (days)	Comments related to mowing and other maintenance
Bemidji	2020	3.25	8.3	6	22.6	
Brainerd	2019	3.25	8.3	7	18.3	
Brainerd	2020	3.25	8.3	9	17.0	
Chatfield	2019	3.25	8.3	6	29.2	Plots were mown infrequently in both growing years due to little aboveground growth from drought conditions.
Chatfield	2020	3.25	8.3	7	29.3	
Duluth	2020	3.25	8.3	5	23.5	
E. G. Forks	2019	3	7.6	6	20.6	
E. G. Forks	2020	3	7.6	10	12.0	Municipality mowed the plots every 10-14 d at 7.6 cm. Their heavy mowers resulted in some dead grass from the wheel traffic in the center of the plots.
Edina	2020	3.25	8.3	11	15.1	Occasionally the border to the last portion of the plot furthest from the curb was mown by us at 3.75 in (9.5 cm) to avoid scalping the grass in the plot due to the change in contour. After mowing ceased by us, the municipality began mowing this section of the plots close to 2 in (5 cm).
Fergus Falls	2019	3.25	8.3	7	19.5	
Fergus Falls	2020	3.25	8.3	9	16.8	
Grand Rapids	2019	3.25	8.3	6	25.4	Grand Rapids municipality mowed plots three times total over the period of data collection (2019-2020). Each time they mowed it around 1.5–2 in (3.8–5.1 cm) to the detriment of the site.

Research site	Growing year	Mode mowing height (in)	Mode mowing height (cm)	Total number of mows	Average mowing interval (days)	Comments related to mowing and other maintenance
Grand Rapids	2020	3.25	8.3	8	17.9	After we finished all data collection, we observed the municipality was mowing the boulevard at 2 in (5.1 cm) which hindered performance of all grasses disproportionately at this site.
International Falls	2020	3	7.6	10	7.0	Blocks 1-2 were mown by local municipality at a height of 2–2.5 in (5.1-6.4 cm) and block 3 was mown by a homeowner at 3 in (7.6 cm).
Marshall	2019	2	5.1	14	7.0	The nearby golf course mowed this research site approximately every 7 d at 2 in (5 cm) or shorter occasionally. There were some periods where they left it a little taller and mowed it with a push mower.
Marshall	2020	2	5.1	14	7.0	
Roseville	2019	3.25	8.3	7	18.7	This site was mowed once at 2.2 in (5.6 cm) in May 2019.
Roseville	2020	3.25	8.3	9	19.1	
Saint Cloud	2020	3.25	8.3	8	16.1	Starting around 07/23/20, or likely sooner, plots 75-120 were mowed around 1.5–2 in (3.8–5.1 cm). Block 3 was found to have less turfgrass coverage and more crabgrass coverage, likely in part due to poorer mowing practices, but also potentially due to lower organic matter content in this block.
Willmar	2020	3.25	8.3	8	16.1	
Worthington	2020	3.25	8.3	9	23.6	Plots 1–34 were mowed and then sprayed, most likely with a broadleaf herbicide by a lawn care company several days prior to 05/21/20. On a different occasion, several days prior to 11/05/20, plots ~30-60 3 ft from the curb to the sidewalk (1.5 m) were mowed by a resident at 2 in (5.1 cm).

Table 2.7 The date of seeding and sampling of total coverage for all research sites. An NA occurs when sampling did not take place.

Research site	Seeding date	Fall 2018	Spring 2019	Fall 2019	Spring 2020	Fall 2020	Spring 2021
G. Rapids	8/30/18	10/19/18	5/31/19	10/11/19	5/28/20	9/21/20	NA
Brainerd	9/12/18	10/19/18	5/28/19	10/2/19	5/26/20	10/9/20	NA
E. G. Forks	9/13/18	10/18/18	5/29/19	10/10/19	6/2/20	10/2/20	NA
Fergus Falls	9/14/18	10/18/18	5/23/19	10/9/19	5/20/20	10/1/20	NA
Roseville	9/15/18	10/26/18	5/20/19	9/27/19	5/18/20	10/19/20	NA
Marshall	9/17/18	10/25/18	5/15/19	11/1/19	5/6/20	11/6/20	NA
Chatfield	9/18/18	11/1/18	5/10/19	10/30/19	5/7/20	10/30/20	NA
Bemidji	8/26/19	NA	NA	10/16/19	5/27/20	9/18/20	5/21/21
Int. Falls	8/28/19	NA	NA	10/17/19	6/3/20	9/14/20	5/26/21
Duluth	9/6/19	NA	NA	10/18/19	6/5/20	9/25/20	5/25/21
Saint Cloud	9/18/19	NA	NA	10/23/19	5/19/20	10/14/20	5/14/21
Willmar	9/11/19	NA	NA	10/22/19	5/15/20	10/16/20	4/30/21
Edina	8/30/19	NA	NA	10/15/19	5/14/20	10/13/20	4/23/21
Worthington	9/4/19	NA	NA	10/25/19	4/30/20	11/5/20	4/16/21

Table 2.8 Generalized linear mixed effects model (GLMM) summary output with three primary response variables of turfgrass, weed, and bare soil coverage. All response variables are a proportion untransformed and bounded from 0–1. Research site was included as a random effect. The number of experimental sampling units is 7,560 for this analysis (N=7,560). Time is the order of sampling instances. Research sites seeded in 2018 were sampled five times and sites seeded in 2019 were sampled four times. SE is the standard error of the estimate.

	Turfgrass coverage			Weed coverage			Bare soil coverage		
	Estimate	SE	*P*-value	Estimate	SE	*P*-value	Estimate	SE	*P*-value
(Intercept)	-0.78929	0.34404	0.02180	-3.71137	0.36300	<2e-16	1.55864	0.25861	1.67E-09
Season spring	0.24500	0.05550	1.01E-05	-1.02851	0.09944	<2e-16	0.66581	0.07069	<2e-16
Time	0.07398	0.04915	0.13230	0.88029	0.09461	<2e-16	-1.13551	0.07781	<2e-16
Number of species	0.09311	0.05351	0.08190	-0.28536	0.15500	0.06560	-0.14086	0.06258	0.02440
Time: Number of species	0.08161	0.01841	9.33E-06	-0.07169	0.04040	0.07600	-0.02639	0.02950	0.37100

Table 2.9 Linear model with natural log of turfgrass spatial stability. Mean and standard deviation of turfgrass coverage for each seed treatment and time was calculated and then the stability was determined by taking the mean divided by the standard deviation. Coefficient estimates and 95% confidence intervals are back-transformed. There were 360 observations in this analysis.

	Turfgrass spatial stability			
	Estimate	Estimate 2.5%	Estimate 97.5%	*P*-value
(Intercept)	1.52521	1.33213	1.74626	2.29E-09
Seeding year 2019	1.02453	0.94427	1.11161	0.55950
Season spring	1.08830	1.00359	1.18017	0.04080
Time	1.03388	1.00229	1.06647	0.03540
Number of species	1.08259	1.04769	1.11866	2.80E-06

Table 2.10 Linear model with natural log of weed spatial stability plus 0.1. Mean and standard deviation of weed coverage for each seed treatment and time was calculated and then the stability was determined by taking the mean divided by the standard deviation. Coefficient estimates and 95% confidence intervals are back-transformed. There were 360 observations in this analysis.

	Weed spatial stability			
	Estimate	Estimate 2.5%	Estimate 97.5%	*P*-value
(Intercept)	0.40924	0.34830	0.48085	<2e-16
Seeding year 2019	1.01723	0.92302	1.12105	0.72980
Season spring	0.95088	0.86337	1.04726	0.30560
Time	1.38544	1.33515	1.43762	<2e-16
Number of species	0.95823	0.92154	0.99638	0.03230

CHAPTER 3: MINNESOTA ROADSIDE SEED BANKS AND THEIR IMPACT ON A SEEDED TURFGRASS MIXTURE STUDY

3.1 INTRODUCTION

Seeding and maintaining roadsides with turfgrass species reduces visibility impairments, soil erosion, and improves the aesthetics of these areas. Turfgrass establishment could be affected by undesirable species that emerge from the soil seed bank during or after the initial establishment period. The seed bank is defined as the total number and type of viable seeds contained in the soil, but usually there are only a subset of the viable seeds that germinate. Identifying characteristics of a roadside seed bank that may inhibit, limit, or reduce seeded turfgrass coverage would be valuable for practitioners. Important characteristics of a seed bank could be related to the diversity, density, and their interaction. Roadside seed banks, and their effect on seeded vegetation is poorly understood. Understanding the type and abundance of a soil seed bank may inform the design of seeded mixtures for roadsides, seeding timing, and short or long-term maintenance. Therefore, the objectives of this study were to (i) characterize the seed bank from 14 roadside research sites in Minnesota, and to (ii) understand if characteristics of these seed banks affect the weed coverage of seeded turfgrass mixtures.

3.2 MATERIALS AND METHODS

3.2.1 Selection and establishment of field sites

Research site selection, turfgrass seed mixture design, plot preparation, seeding, maintenance, and more detailed field data collection, including percent weed and seeded turfgrass cover, are contained within Chapter 2. Field coverage was evaluated at each research site twice per year using the quadrat-grid intersection method. Sampling occurred once in the spring (Apr.–June) and once in the fall (Sep.–Nov.).

3.2.2 Seed bank sampling and testing

Seed bank soil was collected and composited from each of three blocks (repetitions) at 14 research sites after tilling the roadside area for turfgrass seeding. At sites seeded in fall of 2018, soil was collected by hand skimming the surface at regular distances to a depth of 1-4 in (2.5–10.2 cm) every 16-33 ft (5–10 m). Soil from sites seeded in fall 2019 was collected within three wks after seeding using a cup cutter (Thompson, 1993); a total of five cores were sampled per block to a depth of 2.1 in (5.4 cm) containing a total volume of 29 in^3 (477 cm^3) per core. For improved sampling procedures, the reader is directed to: Bigwood and Inouye (1988); Thompson et al. (1997); and Warr et al. (1993).

After collecting the soil from the field, 2018 and 2019 seed bank soil was vernalized to improve germination (Gross, 1990) in a refrigerator for 146 and 59 d, respectively. The average daily temperature in the refrigerator was approximately 30 ° F (-1 ° C) for 60 d and approximately 45 ° F (-7 ° C) for the remaining duration for fall 2018 soil and 37 ° F (-2.7 ° C) for fall 2019 soil. After vernalizing, samples were allowed to air dry approximately 4 wks at room temperature and then the soil was sieved through a 0.16-in (4-mm) screen. The average weight of soil accounting for each block at each research site with standard deviation was 2.4 ± 0.6 lbs (1073 ± 272 g) and 5.4 ± 0.9 lbs (2465 ± 402 g) at fall 2018 and 2019 sites, respectively. Three subsamples each weighing 0.44 lbs (200 g) were then sampled within each block for a total of 1.3 lbs (600 g) per block and a total of 4 lbs (1800 g) for each research site. That totaled nine experimental units for each of seven research sites for a total of 63 experimental units tested in the greenhouse using the soil emergent method (Thompson & Grime, 1979). Greenhouse containers were chosen with a surface area of 15.5 in^2 (100 cm^2) for the 2018 and 14.7 in^2 (95 cm^2) for the 2019 seed bank testing. This closely approximated a 0.79 in (2 cm) thick layer of sieved field soil (Thompson & Grime, 1979) placed over unsterilized sand, but since testing occurred by weight some samples were slightly more or less than 0.79 in (2 cm). Samples were fertilized one time at a rate of 27.2 N-21.4 P-49.7 K kg ha^{-1} using a 10-18-22 fertilizer (EC Grow Prolinks, EC Grow, Eau Claire, WI) mimicking field fertilization rate. Greenhouse containers were arranged in a completely randomized design and were rotated regularly to account for microclimate differences in the greenhouse. Unseeded control pots were also included to identify if unsterilized sand contained any weed seeds.

For the duration of the experiment the greenhouse had an average daily high of 27.7 ° C and low of 18.7 ° C for fall 2018 and 27.0 ° C and 19.7 ° C for fall 2019 sites. A total of 16 hrs of light was supplied from natural and supplemental sources each day. Seedling emergence was evaluated weekly for a 12-week period (Vakhlamova et al., 2016), and only vascular plants were identified. A photo shows the experimental setup and testing of soil from sites seeded in 2019 (Figure 3.1). We found significant moss buildup over time that affected samples from some research sites and may have limited some seedling emergence. If seedlings could not be identified, they were transplanted and allowed to flower. Plant species nomenclature, characteristics, and identification was primarily based on Chadde (2019) with the exception of *Juncus* spp. identification, which was based on Känzig-Schoch et al. (2007) and Smith (2018). One seedling, Silvery cinquefoil (*Potentilla argentea* L.), emerged from the control tray from the fall 2018 test and so that species was not counted if it emerged within that testing year. Small dropseed (*Sporobolus neglectus* Nash) was not distinguished from poverty dropseed (*Sporobolus vaginiflorus* (Torr.) Wood). Additionally, five research sites from the seven sites seeded in fall 2019 had one non-seeded field control plot to compare aboveground vegetation with seed bank results, if desired.

3.2.3 Soil sampling and analysis

Soil samples were collected from research sites in Aug. or Sep. Soil was collected before tillage by sampling 15–20 cores in each block in a zig-zag pattern at each site to a depth of 3.9–5.9 in (10–15 cm).

All soil samples were composited by block within each site and analyzed for pH, soil texture, organic matter, extractable phosphorus, K, saturated paste extract electrical conductivity, Fe, and Mn. Additionally, Zn and Cu were included in soil tests due to their relationship of emergence and abundance of common weedy roadside vegetation (Bae et al., 2015). Total bulk density was determined within all three blocks at each site by utilizing the water volume determinant excavation method (Page-Dumroese et al., 1999). Soil analyses by block are shown in Table 3.1. Additional soil sampling details and results are included in Chapter 2.

3.2.4 Statistics

Seedling counts for each subsample within each research site and block are shown in Table 3.2. The Chao species richness was calculated for each site to estimate the total number of species that each site likely contained in the seed bank while accounting for sampling limitations (Chao, 1984). The probability of an interspecific encounter (PIE) was calculated to have a standardized evenness measurement (Gotelli, 2008; Hurlbert, 1971). Seedling density was calculated by controlling for the total soil bulk density and expressing the value as seedlings gal^{-1} to account for variation in seed bank sampling depths between testing years (Stark et al. 2003). Expressing seedling counts by volume avoids the dependence on sampling depth for the seedlings per area reporting (Thompson et al., 1997), yet it may not be as intuitive as seedlings per area commonly reported. Species density was also calculated (James & Wamer, 1982).

All analyses were performed using the open-source software R (R Core Team, 2021). A non-metric multidimensional scaling (NMDS) was applied using the *metaMDS* function to spatially visualize the rank-order differences in species abundance and research sites. The *metaMDS* function and all subsequent functions for multivariate analysis were contained within the vegan package (Oksanen et al., 2020) and used a Bray-Curtis dissimilarity index. The *metaMDS* function was set with two dimensions with 100 attempts to find a solution, and the values were autotransformed to improve the results with a square root and then a Wisconsin double standardization transformation applied. The dimensions were set so the stress value of the NMDS did not exceed 0.2. The ordination analysis only included plants identified to at least the genus level. A PERMANOVA analysis was performed using the *adonis2* function to identify if there were differences in seed bank species composition by region. The regions tested in the analysis were ecoregion level two and three (Omernik, 1987; Omernik & Griffith, 2014), one of the eight different MnDOT regions, and a custom separation from NNE sites to SSW sites, which included East Grand Forks classified by NNE sites and Fergus Falls and St. Cloud included within the SSW sites (Figure 2.1). The homogeneity of variance assumption between regions was assessed by using the *vegdist* function on the matrix of the species composition data by site, and then applying the *betadisper* function.

A generalized linear model (GLM) with field weed coverage (%) as the response variable was conducted using the *glm* function with family set to binomial. All main effect explanatory variables included in the full model consisted of seeding year (2018 or 2019), time; defined as the order of vegetation sampling (1–5), research site, and the primary covariates were seed bank seedling density (count L^{-1}), Chao species density (count L^{-1}), observed species density (count L^{-1}), field turfgrass cover (%), and field bare soil cover (%). Interaction effects included time by observed seed bank species density, seeding year by time, time by seedling density, and time by Chao species density. To identify the final model, both a forward and backward stepwise model selection procedure was performed using the *stepAIC* function contained in the MASS package (Venables & Ripley, 2002). McFadden pseudo-R^2 values were calculated (McFadden, 1973) and used in addition to AIC score to compare model selection. Results are discussed in terms of odds, instead of log-odds, which is found from exponentiating the coefficient from the GLM table.

3.3 RESULTS

3.3.1 Seed bank characteristics

The total number of emerged seedlings from the soil seed bank sampled from the field and emerged in the greenhouse ranged by site from 37 (East Grand Forks) to 318 (Marshall), with a total of 74 species identified across all sites (Appendix A). Observed species richness ranged from 10 at Edina to 21 at Roseville. Chao estimated species richness was found to double or more than triple the observed species richness at some research sites (Table 3.3), which suggests significant sampling limitations at some sites. The probability of an interspecific encounter was the lowest at Marshall and Roseville was next highest, indicating more dominance of seedlings by a few species (Table 3.3) at those two sites. Seedling density (seedlings gal^{-1}) ranged from 87 (East Grand Forks) to 791 (Marshall), respectively, and this value was calculated by controlling for bulk density, since seed bank testing occurred by weight, resulting in sites with lower bulk density containing greater volume of soil tested. Observed species density was highest for Bemidji (60 species gal^{-1}) and lowest for Edina (30 species gal^{-1}). The Chao estimated species richness was highest for Grand Rapids (121 species gal^{-1}) and lowest for East Grand Forks (34 species gal^{-1}) (Table 3.4).

The average proportion of native seedlings that emerged (0.17) was much less compared to non-native (0.74), yet the proportion was more similar for emerged species that were native (0.41) compared to non-native species (0.48) (Table 3.5). Similarly, the proportion of annual seedlings dominated most sites, but in terms of species number, the disparity between annuals and perennials was much smaller (Figure 3.2). The top five species that appeared at the most sites were poverty dropseed found at 10 sites, large crabgrass found at nine sites, and then broadleaf plantain (*Plantago major* L.), smooth crabgrass, and Kentucky bluegrass each found at eight sites. The top five most abundant species by proportion were large crabgrass (0.35), black medic (*Medicago lupulina* L.) (0.09), smooth crabgrass (0.08), broadleaf plantain (0.04), and common purslane (*Portulaca oleracea* L.) (0.04). The PERMANOVA analysis found a significant difference only between the NNE-SSW separation ($F_{1,12}$=2.18, R^2=0.15, P=0.003). The NMDS results are shown for species separation in (Figure 3.3A) and research site separation in (Figure 3.3B).

3.3.2 Identifying the potential impact of the seed bank on field plot weed coverage over time

The results of the generalized linear model indicated significant main and interaction effects on weed cover measured in the field plots. The planting year by time interaction suggests that weed coverage in the field was more similar at sites seeded in 2019 as time progressed compared to sites seeded in 2018 (odds increase by 1.25 times for each increment of time). The seeding year coefficient main effect odds estimate decreases 0.49 times illustrating that there is less weed coverage at sites seeded in 2019. While holding the other parameters constant, with each additional increment of time within a year, the odds of weed coverage on field plots increased 1.54 times (Table 3.6). With each additional increment of turfgrass or bare soil coverage, the odds of weed coverage decreased by 0.002 and 0.001 times, respectively (Table 3.6). Observed seed bank species density was found to increase the odds of weed coverage on field plots by 1.11, but the significant interaction effect indicated that the effect decreased over time (odds decrease by 0.97 times for each additional increment of time) (Table 3.6). Chao estimated species density and seedling density were not included in the final model based on the stepwise procedure as most of the deviance in weed cover was explained by turfgrass and bare soil coverage, then time.

3.4 DISCUSSION

We found differences in many seed bank characteristics, despite all sites being relatively well-drained roadsides in Minnesota (Table 3.3-3.4; Figure 3.2-3). Most surprising was that weed coverage in plots was not impacted by seed bank seedling density, despite, for example, measuring 9 times higher seedling density at Marshall compared to East Grand Forks (Table 3.4). When examining the covariates of the generalized linear model graphically, the average weed coverage over time at each site plotted as a function of turfgrass cover showed a strong negative trend with more turfgrass cover resulting in less weed cover (Figure 3.4); likewise, more bare soil cover resulted in more weed coverage up to 50%, but then decreased, since our coverage is constrained between 0–1 (Figure 3.4). Weed cover in field plots showed little to no trend as a function of the seed bank seedling density (Figure 3.5), Chao estimated species richness (Figure 3.6), and observed species density (Figure 3.6). Seed bank characteristics not having a significant impact on weed coverage may not be surprising, since it is well documented that the seed bank characteristics usually do not accurately reflect the concurrently growing aboveground vegetation at a site (Bekker et al., 1997; Coffin & Lauenroth, 1989; Pekas & Schupp, 2013; Skowronek et al., 2014; Thompson, 1986; Thompson & Grime, 1979). We were also surprised that observed seed bank species density was included in the final stepwise model rather than Chao estimated seed bank species richness, thought to be a closer approximation to the actual number of species at each site.

The results of the NMDS suggest that there is a significant difference in roadside seed bank composition between NNE and SSW sites. From examining the NMDS, rush species are on the far left side and crabgrass (*Digitaria* spp.) are on the right (Figure 3.3), so we hypothesize the interaction between warmer climate normal air temperatures (Table 3.7) is likely causing the separation with greater abundance of warm-season annual species in warmer sunny areas of the state. The abundance of large crabgrass was very high at Marshall; this site was located adjacent to the golf course and was maintained regularly with above-average mowing intervals and lower than average heights of cut for roadside vegetation, conditions known to favor crabgrass abundance (Davis, 1958). Additionally, Marshall contained 12 observed species, one of the lowest, which also may have been due to intensive mowing, since it has been shown that increasing management intensity reduces species richness and increases seed bank seedling density (Auestad et al., 2013; Dölle & Schmidt, 2009).

Several limitations may have influenced the results of this study. Different research sites were affected differently by abiotic factors. For example, Brainerd and Bemidji contained low turfgrass coverage, resulting in high weed and/or bare soil coverage relative to other research sites; therefore, the seed bank characteristics were clearly not the main factor in weed coverage. We also found differences in bulk density at our field sites which could have lessened weed seedling emergence and coverage (Stark et al., 2003).

Previous roadside turfgrass research has found that seeding cool-season mixtures in late summer to early fall is ideal in Minnesota because soil temperatures are high and weed pressure is low (Watkins & Trappe, 2017). Additionally, it is known that the timing of cultivation affects species abundance (Roberts & Ricketts, 1979). We therefore hypothesize if these sites were seeded in early summer, then seed bank characteristics could have likely played a more significant and long-lasting effect. We conclude that roadsides that are regularly mowed in Minnesota contain mostly undesirable ruderal vegetation in the seed bank, but greater richness of native species than expected. The properties of a seed bank are not a major factor impacting weed coverage over time. We found that the most significant factor to reduce weed coverage is to maintain adequate seeded turfgrass coverage over time.

Figure 3.1 Seed bank soil being tested for sites seeded in 2019. Different densities and ratios of plant types are evident.

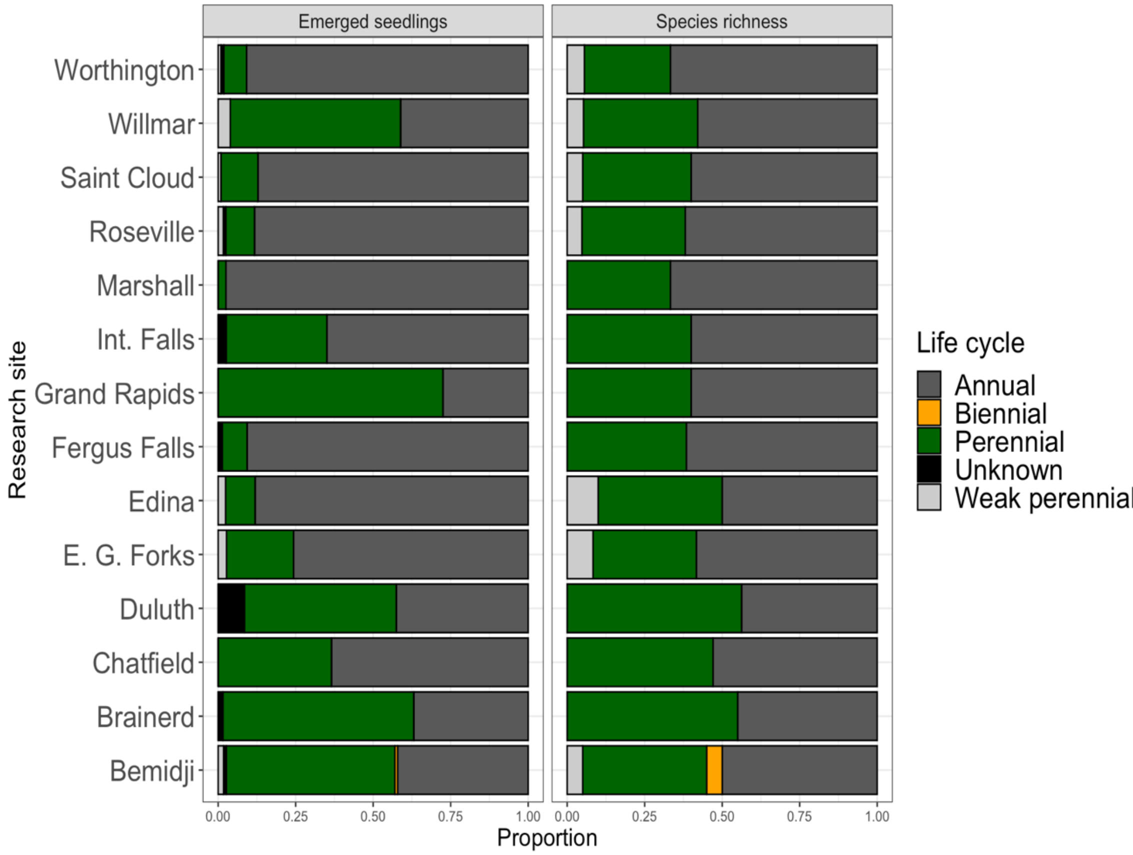

Figure 3.2 Proportion of the count of the emerged seedlings and the number of observed species at each research site classified by life cycle. Unknown represents an emerged seedling that died before it could be identified. Carpet vervain (*Verbena bracteata* (Lag. Rodr.)) and common dandelion (*Taraxacum officinale* G.H. Weber) were classified as weak perennial.

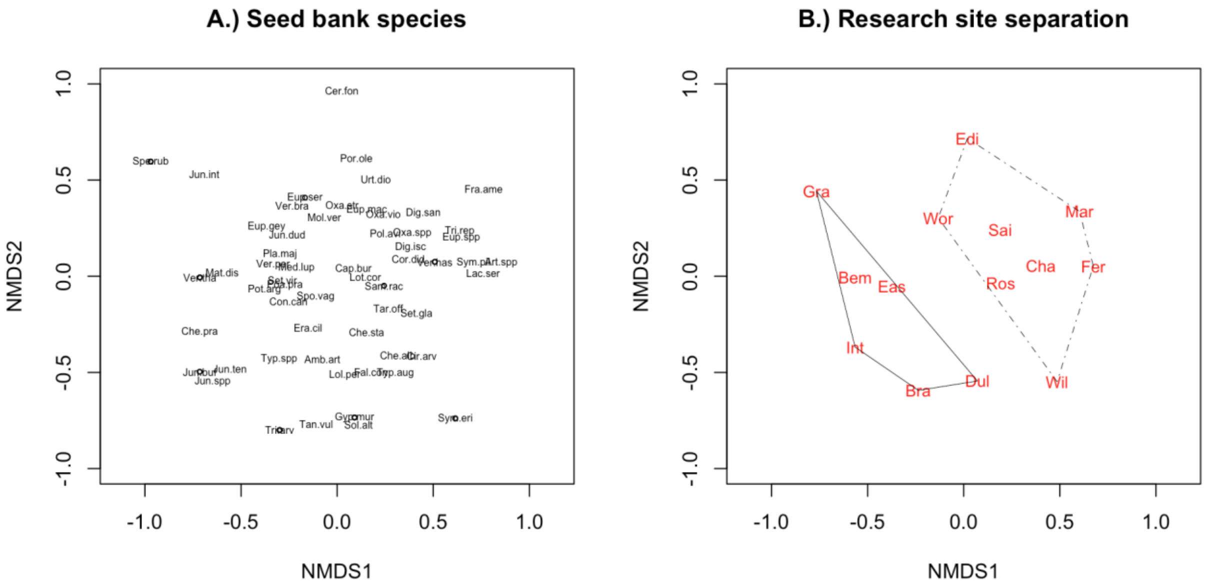

Figure 3.3 NMDS ordination plot of different vascular plants identified to at least the genus level (A) and north-south separation in species composition based on PERMANOVA results (Stress=0.199) (B). Labels in (A) are the first five letters of the genus followed by the first three letters of the species name, and circles behind some labels indicate there are multiple species in that same ordination space. Labels in (B) correspond to different research sites (Bem=Bemidji, Bra=Brainerd, Cha=Chatfield, Dul=Duluth, Eas=East Grand Forks, Edi=Edina, Fer=Fergus Falls, Gra=Grand Rapids, Int=International Falls, Mar=Marshall, Ros=Roseville, Sai=Saint Cloud, Wil=Willmar, and Wor=Worthington).

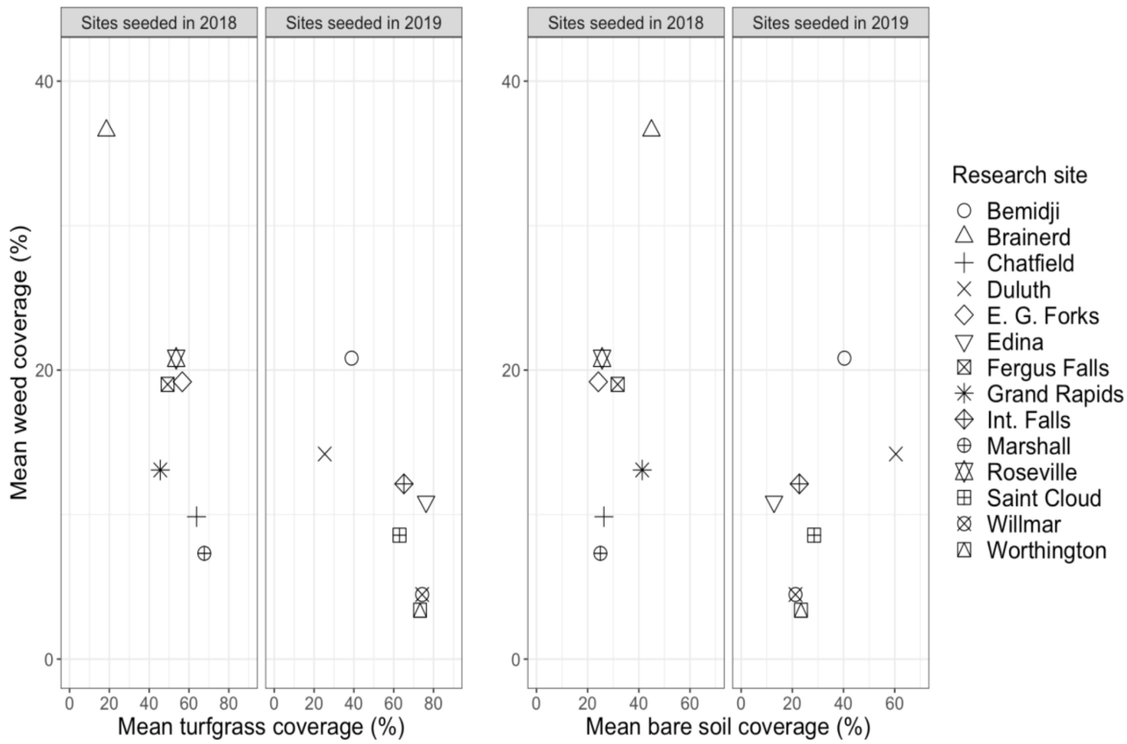

Figure 3.4 Mean weed coverage as a function of turfgrass and bare soil coverage averaged over all sampling times within each research sites. Seeding year is shown faceted in both graphs. The three coverage variables (weed, turf, and bare soil) changed over time at these different research sites.

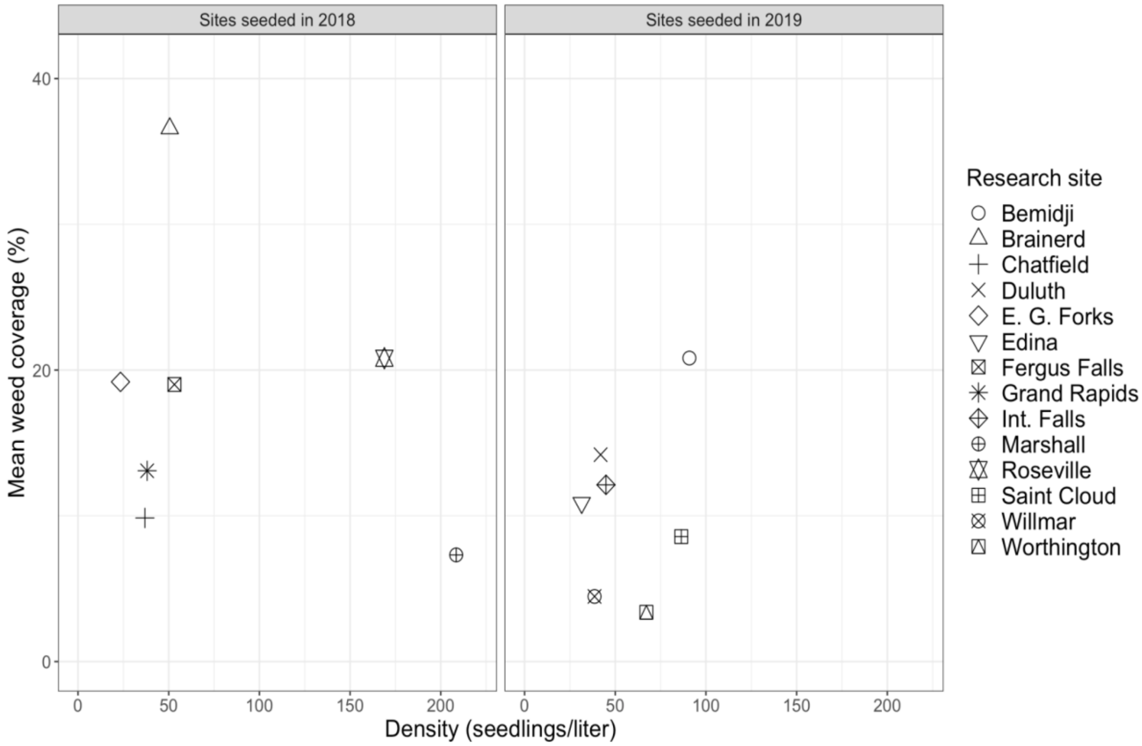

Figure 3.5 Mean weed coverage as a function of seedling density at each research site. Mean weed cover is an average across all sampling instances.

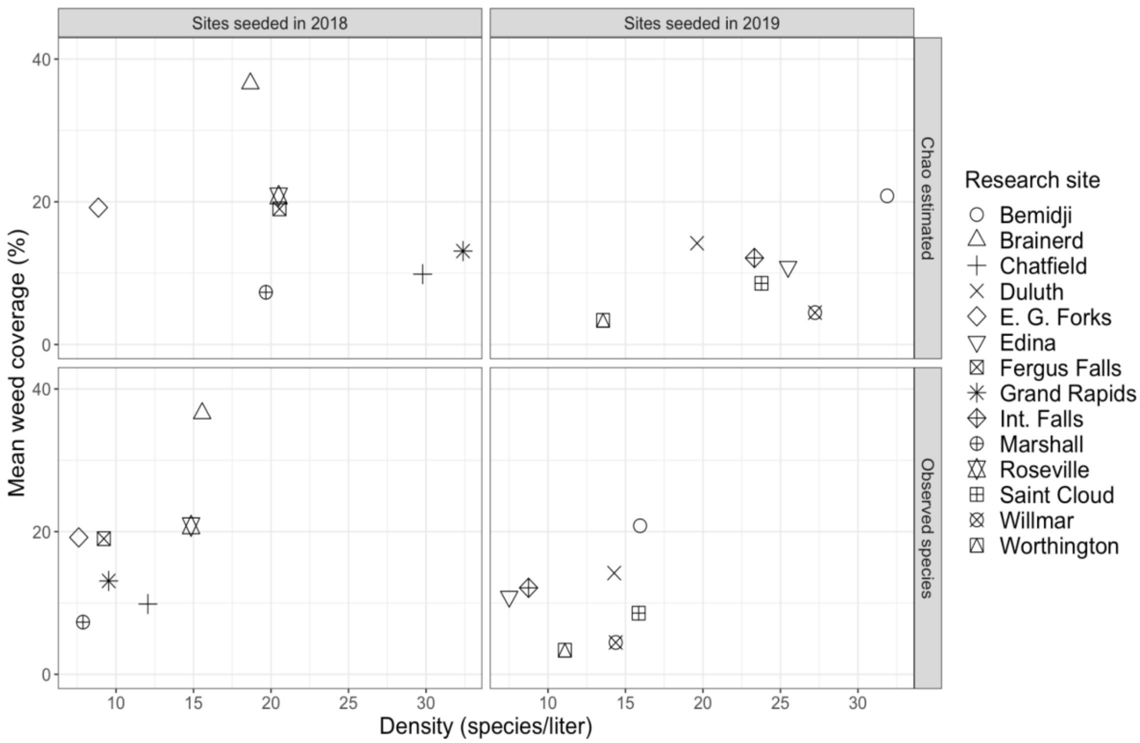

Figure 3.6 Mean weed coverage as a function of Chao estimated and observed species density at each research site.

Table 3.1 Soil characteristics for each block within the fourteen research sites. The University of Minnesota soil testing laboratory analyzed all samples using standard methods.

Research site	Block	Bray P[a]	Olsen P[a]	K[c]	OM	pH	Sat. elect. conductivity (mmhos cm^{-1})[c]	Sand (%)	Silt (%)	Clay (%)	Soil textural class[b]	Fe[ac]	Mn[ac]	Zn[ac]	Cu[ac]
Bemidji	1	33	NA	74	2.0	7.3	1.0	70.0	10.0	20.0	SCL-SL	17.27	5.40	3.30	0.37
Bemidji	2	32	NA	64	1.7	7.3	1.1	70.0	11.3	18.8	SL	17.03	5.63	2.34	0.34
Bemidji	3	50	NA	108	2.5	7.3	1.1	68.7	10.0	21.3	SCL	23.30	5.29	2.88	0.32
Brainerd	1	31	9	82	3.30	7.4	0.9	70	9	21	SCL	56.64	5.21	42.45	10.34
Brainerd	2	25	7	64	3.10	7.4	0.7	71	8	21	SCL	76.27	4.47	46.33	14.17
Brainerd	3	30	11	89	2.90	7.4	0.6	73	5	23	SCL	42.48	4.34	41.08	18.55
Chatfield	1	26	14	166	3.10	7.4	0.6	50	18	33	SCL	27.59	8.30	1.39	0.43
Chatfield	2	26	13	117	2.50	7.5	0.8	53	16	31	SCL	23.91	8.06	1.64	0.40
Chatfield	3	25	9	116	2.50	7.6	0.9	55	14	31	SCL	17.48	8.16	1.26	0.30
Duluth	1	7	4	56	1.7	7.5	1.4	52.5	25.0	22.5	SCL	53.65	8.74	2.08	4.73
Duluth	2	11	5	49	2.6	7.5	1.5	53.8	23.7	22.5	SCL	54.59	5.73	2.33	4.71
Duluth	3	12	5	63	3.5	7.5	2.0	58.8	20.0	21.2	SCL	62.97	4.20	6.81	4.66
E. G. Forks	1	0	14	297	5.20	7.8	0.7	5	49	46	Silty clay	10.12	5.84	1.92	1.36
E. G. Forks	2	0	8	226	5.00	7.9	0.6	4	49	48	Silty clay	10.48	6.81	1.64	1.42
E. G. Forks	3	0	9	196	4.70	7.9	0.6	3	48	49	Silty clay	9.83	6.87	1.57	1.43
Edina	1	30	NA	89	5.6	7.2	1.3	51.3	23.8	25.0	SCL	42.43	4.21	5.96	1.01
Edina	2	23	NA	64	6.0	7.2	1.6	47.5	26.2	26.2	SCL	40.06	4.61	6.56	1.09
Edina	3	25	NA	56	5.8	7.2	1.4	48.8	26.2	25.0	SCL	40.47	5.25	7.70	1.22
Fergus Falls	1	11	5	264	5.20	7.9	1.1	48	21	31	SCL	14.82	5.12	6.37	1.19

Research site	Block	Bray P[a]	Olsen P[a]	K[c]	OM	pH	Sat. elect. conductivity (mmhos cm^{-1})[c]	Sand (%)	Silt (%)	Clay (%)	Soil textural class[b]	Fe[ac]	Mn[ac]	Zn[ac]	Cu[ac]
Fergus Falls	2	20	10	218	5.30	7.9	1.0	51	19	30	SCL	12.54	3.87	6.32	1.15
Fergus Falls	3	16	7	210	4.80	7.9	0.8	52	19	29	SCL	11.92	4.63	5.83	1.12
G. Rapids	1	39	12	61	1.80	7.4	1.0	59	19	23	SCL	49.00	7.25	2.76	0.85
G. Rapids	2	36	9	56	1.50	7.4	0.8	64	15	21	SCL	41.93	7.01	2.47	1.07
G. Rapids	3	40	11	61	2.20	7.5	0.6	58	21	21	SCL	38.05	7.11	3.62	1.17
Int. Falls	1	4	4	145	5.7	7.5	1.3	38.7	21.3	40.1	Clay	42.03	2.54	2.68	1.27
Int. Falls	2	5	4	146	5.3	7.6	0.7	34.9	26.3	38.8	Clay loam	30.78	1.74	2.69	1.08
Int. Falls	3	5	4	97	8.9	7.5	1.3	50.0	18.8	31.3	SCL	47.20	1.80	5.09	1.21
Marshall	1	10	15	249	4.00	7.6	0.4	35	24	41	Clay	21.82	8.04	3.22	1.10
Marshall	2	7	10	175	3.80	7.8	0.5	34	24	43	Clay	19.84	7.43	3.73	1.19
Marshall	3	9	8	186	4.20	7.9	0.5	34	23	43	Clay	19.09	7.39	3.28	1.27
Roseville	1	14.5	6.5	65	6.10	7.9	0.7	60	15	25	SCL	42.95	3.95	15.80	2.63
Roseville	2	13	6	87	4.60	8.0	0.6	69	6	25	SCL	25.18	3.96	11.89	2.59
Roseville	3	16	6	71	4.70	7.8	0.6	56	19	25	SCL	26.00	3.75	10.76	2.54
Saint Cloud	1	40	NA	139	3.1	6.4	1.5	51.2	20.0	28.8	SCL	116.36	10.91	3.53	0.75
Saint Cloud	2	42	NA	135	2.6	7.0	1.2	58.7	15.0	26.3	SCL	47.56	7.80	1.88	0.49
Saint Cloud	3	58	NA	153	2.4	7.2	1.5	65.0	11.3	23.8	SCL	29.15	6.40	1.85	0.36
Willmar	1	2	9	166	3.6	7.5	1.7	46.3	23.7	30.0	SCL	17.44	4.35	9.24	1.21
Willmar	2	2	8	181	3.4	7.5	1.5	37.5	30.0	32.5	Clay loam	15.64	3.86	3.91	0.88
Willmar	3	5	NA	202	3.3	7.4	1.4	43.7	25.0	31.3	Clay loam	20.13	4.11	4.76	0.97

Research site	Block	Bray P[a]	Olsen P[a]	K[c]	OM	pH	Sat. elect. conductivity (mmhos cm^{-1})[c]	Sand (%)	Silt (%)	Clay (%)	Soil textural class[b]	Fe[ac]	Mn[ac]	Zn[ac]	Cu[ac]
Worthington	1	26	NA	166	5.1	7.2	1.5	20.0	36.3	43.8	Clay	26.91	7.18	2.83	0.86
Worthington	2	18	NA	161	4.8	7.4	0.4	16.3	38.7	45.0	Clay	29.29	7.59	2.75	1.15
Worthington	3	19	NA	183	5.2	7.3	0.6	12.5	43.7	43.7	Silty clay	30.98	7.75	3.07	1.03

[a] Units of mg kg^{-1}

[b] SCL = Sandy clay loam, SL= Sandy loam,

[c] Additional 20 cores of soil samples were collected and composited within each block at each research sites seeded in 2018 between June–Aug. 2020 and were tested for heavy metals and saturated paste extract electrical conductivity.

Table 3.2 Emerged seedlings within each subsample of each block at each research site. A total of 1,375 seedlings emerged from the seed bank analysis in this study from both seeding years; 826 from sites seeded in 2018 and 549 from sites seeded in 2019. Sampling and preparation methods varied slightly between seeding years.

		Block								
			1			2			3	
Research site	Seeding year	1	2	3	1	2	3	1	2	3
Brainerd	2018	19	3	16	5	8	0	7	5	2
Chatfield	2018	2	4	1	5	3	5	10	12	10
East Grand Forks	2018	7	5	4	5	2	3	2	3	6
Fergus Falls	2018	9	6	12	11	4	4	11	10	8
Grand Rapids	2018	1	3	3	10	7	7	3	2	4
Marshall	2018	39	69	44	54	65	33	5	3	6
Roseville	2018	42	27	26	34	13	34	24	18	21
Bemidji	2019	16	18	15	13	8	9	10	12	13
Duluth	2019	2	3	2	4	9	8	4	9	6
Edina	2019	4	3	0	12	8	3	2	6	4
International Falls	2019	21	6	15	7	9	13	3	0	3
Saint Cloud	2019	8	14	8	16	18	7	14	11	13
Willmar	2019	2	6	4	9	10	5	5	7	3
Worthington	2019	16	14	13	7	5	3	15	19	17

Table 3.3 The total number of seedlings, observed species, and Chao estimated species that emerged from the seed bank soil at each research site. Chao estimated species richness is based on the number of seedlings within a species at a research site that emerged once or twice.

		Species richness		Evenness
Research site	Total emerged seedlings	Observed	Chao estimated	PIE[a]
Bemidji	114	20	40	0.85
Brainerd	65	20	24	0.89
Chatfield	52	17	42	0.86
Duluth	47	16	22	0.92
East Grand Forks	37	12	14	0.83
Edina	42	10	34	0.57
Fergus Falls	75	13	29	0.67
Grand Rapids	40	10	34	0.60
International Falls	77	15	40	0.83
Marshall	318	12	30	0.22
Roseville	239	21	29	0.55
Saint Cloud	109	20	30	0.87
Willmar	51	19	36	0.89
Worthington	109	18	22	0.80

[a] Probability of an interspecific encounter (PIE) ranges from 0–1 to identify the evenness within a research site (e.g. 1 = each individual seedling is a unique species, 0 = each individual seedling is the same species).

Table 3.4 Density estimates for average total soil bulk density, seedling and observed species richness, and Chao estimated species richness from the soil seed bank from each research site.

	Density			
Research site	Soil bulk[a] ($g\ cm^{-3}$)	Seedling[b] (seedlings L^{-1})	Obs. species[c] (species L^{-1})	Chao estimated[d] (species L^{-1})
Bemidji	1.43	90.87	15.94	31.88
Brainerd	1.40	50.56	15.56	18.67
Chatfield	1.28	36.88	12.06	29.78
Duluth	1.61	41.92	14.27	19.62
E. G. Forks	1.14	23.42	7.59	8.86
Edina	1.35	31.49	7.50	25.49
Fergus Falls	1.28	53.14	9.21	20.55
G. Rapids	1.71	38.10	9.53	32.39
Int. Falls	1.05	44.89	8.74	23.32
Marshall	1.18	208.51	7.87	19.67
Roseville	1.27	168.89	14.84	20.49
Saint Cloud	1.43	86.39	15.85	23.78
Willmar	1.36	38.57	14.37	27.23
Worthington	1.11	67.15	11.09	13.55

[a] Total coarse bulk density includes unsieved coarse fragments.
[b] Density (seedlings L^{-1}) was calculated by taking the total number of seedlings at each research site and dividing that by 4 lbs (1800 g) (for that was the total amount of weight tested at each site then multiplying that value by the mean total bulk density at that site and then multiplying by 1000 to result in seedlings L^{-1}.
[c] Observed species density was calculated by taking the number of observed species at each research site divided by the total number of seedlings and then multiplying that value by the density in seedlings L^{-1}.
[d] Chao estimated species density was calculated by taking the Chao species richness for each site (Chao, 1984) and then dividing that value by the total number of seedlings and then multiplying that value by the density in seedlings L^{-1}.

Table 3.5 Number of seedlings and observed species at each site from the soil seed bank classified by origin. Seedlings classified as cryptic refers to specimens that do not have a clear origin or specimens that were not identified to the species level (i.e., the genus level contains native and non-native species), or samples that died before they could be identified.

	Species origin					
	Native		Non-native		Cryptic	
Research site	Count	Species richness	Count	Species richness	Count	Species richness
Bemidji	0.28	0.50	0.65	0.45	0.07	0.05
Brainerd	0.34	0.50	0.23	0.25	0.43	0.25
Chatfield	0.17	0.41	0.67	0.47	0.15	0.12
Duluth	0.32	0.38	0.49	0.38	0.19	0.25
E. G. Forks	0.46	0.25	0.38	0.50	0.16	0.25
Edina	0.17	0.60	0.83	0.40	0.00	0.00
Fergus Falls	0.07	0.31	0.64	0.62	0.29	0.08
Grand Rapids	0.10	0.30	0.88	0.60	0.03	0.10
Int. Falls	0.35	0.53	0.40	0.27	0.25	0.20
Marshall	0.03	0.33	0.92	0.50	0.06	0.17
Roseville	0.10	0.38	0.88	0.52	0.02	0.10
Saint Cloud	0.24	0.45	0.76	0.55	0.00	0.00
Willmar	0.24	0.26	0.76	0.74	0.00	0.00
Worthington	0.17	0.44	0.82	0.50	0.02	0.06
Average[a]	0.17	0.41	0.74	0.48	0.09	0.11

[a] Not the average calculated from the proportions listed in this table, but the average incorporating all seedlings.

Table 3.6 Generalized linear model summary results with weed coverage (%) as the response variable. Seeding year coefficient distinguishes the research sites seeded in separate seeding years. Time represents the order of vegetation sampling that each site was sampled (sites seeded in 2018 have a total of five sampling instances and sites seeded in 2019 have a total of four sampling instances). All three coverage variables (weed, turfgrass and bare soil) are a proportion bounded from 0–1. Observed seed bank species density is tested in units of count per liter.

Coefficients	Estimate	SE	z value	Pr(>|z|)
(Intercept)	1.59152	0.54935	2.897	0.00377
Seeding year 2019	-0.70069	0.29845	-2.348	0.01889
Time	0.43612	0.13895	3.139	0.0017
Turfgrass coverage	-6.39802	0.20146	-31.758	<2E-16
Bare soil coverage	-6.57867	0.27494	-23.928	<2E-16
Observed seed bank species density	0.10011	0.04162	2.405	0.01617
Time:Observed seed bank species density	-0.02552	0.01141	-2.236	0.02533
Seeding year 2019:Time	0.22727	0.08888	2.557	0.01056

Null deviance: 2312.3 on 7559 degrees of freedom. Residual deviance: 245.4 on 7552 degrees of freedom. McFadden pseudo R^2 value = 0.89.

Table 3.7 Climate normal (1991-2020) weather data for all 14 research sites from the nearest station containing the most complete dataset. TMAX = temperature maximum, TMIN = temperature minimum, PRCP = rainfall precipitation, SNOW = snowfall precipitation.

Research site	TMAX[a]	TMIN[a]	PRCP[b]	SNOW[b]
Bemidji	10.28	-0.97	689.82	1194.13
Brainerd	11.26	-1.06	772.19	1223.59
Chatfield	12.18	2.09	880.83	1341.87
Duluth	9.52	-0.44	792.07	2291.96
East Grand Forks	10.43	-0.51	576.02	1264.55
Edina	12.97	3.30	802.62	1302.83
Fergus Falls	10.45	-1.18	598.96	493.48
Grand Rapids	9.84	-1.49	698.98	1087.06
Int. Falls	9.41	-2.97	644.25	1855.52
Marshall	13.25	1.98	734.43	1149.52
Roseville	12.87	2.79	835.42	731.58
Saint Cloud	11.97	0.37	723.50	1231.54
Willmar	11.45	0.54	775.01	1204.22
Worthington	12.52	1.34	783.05	1190.62

[a] Average of average monthly climate normals in units of degrees Celsius.
[b] Sum of average monthly precipitation in units of mm.

CHAPTER 4: IDENTIFYING ROADSIDE TURFGRASS SEEDING CLUSTERS BASED ON DIFFERENT WEATHER AND SOIL FACTORS

4.1 INTRODUCTION

MnDOT currently recommends different native vegetation mixtures based on region within the state (MacDonagh & Hallyn, 2010). Turfgrass seed mixtures have recommendations only on a statewide basis (MnDOT, 2014) and do not account for the tremendous ecological differences that are found in the state of Minnesota. Several authors have identified the importance of regionally adapted roadside vegetation (Friell et al., 2015; Tinsley et al., 2006), but only a few have tested different mixtures across sites. Engelhardt (2016) conducted a literature review, and separated four regions in Maryland, and then Engelhardt and Ratliff (2019) went on to test different mixtures within three regions in a field trial, but had difficulty validating regions due to testing at too few research sites. In West Virginia, Hopkinson et al. (2018) assessed if different roadside mixtures are necessary for different elevations and they found that the high elevation site had poorer soils and cooler temperatures, but their proposed high-elevation mixture did not prove to be better than the other mixtures.

Roadside turfgrass experiments have found different species performances in different weather and climate conditions (Brown et al., 2010; Diesburg et al., 1997; Friell et al., 2012; Henslin, 1982; Hottenstein, 1969; Mintenko et al., 2002; White & Smithberg, 1972) and in soil physical and chemical characteristics (Duell & Schmit, 1975; Foote et al., 1978; Henslin, 1982; Hopkinson et al., 2016; Martin & Kaufman, 1970; Watkins et al., 2019). Considering and grouping sites based on both climate and soil characteristics will be referred as *clustering*, and this form of classification has been widely used in research (Milligan & Cooper, 1987). Clustering could improve roadside turfgrass mixtures recommendations by accounting for important plant growing factors affecting roadside vegetation.

We hypothesize there is enough variation in soils and climate to have different seeding clusters in the state of Minnesota to improve roadside turfgrass seed mixture recommendations. Therefore, the objective of this research was to identify if there should be different roadside turfgrass seeding clusters incorporating both weather and soil variables in Minnesota, and to validate clustering by assessing the results of our experiment (see Chapter 2) testing turfgrass species and mixtures across the state of Minnesota.

4.2 MATERIALS AND METHODS

4.2.1 Research sites and field method

The research sites, species that were selected, germination testing, treatment and mixture design, soil sampling and testing, supplemental irrigation during establishment, plot maintenance, and data collection can be found in Chapter 2.

4.2.2 Weather data

An on-site weather station was installed at all sites close to the seeding date and kept at each site until at least the following summer (7 stations in total). Data were recorded by a WatchDog 1400 data logger (Spectrum Technologies, Aurora IL) every thirty minutes. The station recorded soil moisture, temperature, and electrical conductivity using a WaterScout SMEC 300 probe (Spectrum Technologies, Aurora IL) inserted 2 in (5 cm) into the soil layer. The probe was oriented horizontally at sites seeded in 2018 and vertically at sites seeded in 2019. Average soil moisture was calculated by averaging all available soil moisture data within each location recorded by the SMEC probe. Precipitation was recorded with a tipping bucket calibrated before installation of sites seeded in 2018. Tipping buckets were subject to clogging from excess debris and values were thus skewed at some sites and not used in further analysis. Labjack Digits-TLH (Sahasra Electronics, India) were also inserted 2 in (5 cm) into the soil layer in the middle of each block (plot 20, 60, and 100) to monitor soil temperature. Digits recorded soil temperature every six hrs at sites seeded in 2018 and hourly for sites seeded in 2019.

We gathered daily maximum and minimum temperature, rainfall precipitation, snow precipitation, and snow depth from the nearest professionally collected weather station (Table 4.1) (NOAA), since on-site weather stations had inconsistencies in rainfall precipitation and air temperature. A thirty-year climate normal dataset (1991-2020) was calculated (Table 3.7) for each of these stations to compare observed weather variables during the length of the experiment to climate normals, to show how representative the climate of that research site was to normal conditions. The number of growing degree days was calculated using a base temperature of both 32 and 50 ° F (0 and 10 ° C) by taking the summation of the sum of the daily maximum and minimum temperature and dividing by two, then subtracting the base temperature.

4.2.3 Statistics

R software was used for all data processing and analysis (R Core Team, 2021). Average turfgrass coverage, moisture characteristics, and soil physical and chemical characteristics were compared among each research site using a Fisher's least significant difference (LSD) test with the *LSD.test* function in the agricolae package and no p-value correction was applied (de Mendiburu, 2020). To identify distinct roadside seeding clusters, we gathered all weather and soil variables that are thought to have a significant effect on turfgrass coverage on roadsides over time. Weather variables collected from the on-site station included minimum winter soil temperature, number of days of soil temperature below 23 ° F (-5 ° C), and number of days of soil temperature above 95 ° F (35 ° C). Weather variables collected from the nearest professionally collected weather station were the cumulative sum of the total number of growing degree days at base 32 and 50 ° F (0 and 10 ° C), average maximum temperature (TMAX), average minimum temperature (TMIN), sum of rainfall precipitation (PRCP), sum of snowfall precipitation (SNOW), and average snow depth (SNWD) all from weather observed in 2020. Latitude (LAT) was included as a proxy for potential sunlight quantity. The soil variables, which were averaged for each site, included the average moisture from the on-site station (Table 4.2); potential plant available water (Table 4.2); sand, silt, clay, and organic matter (OM); saturated paste extract electrical conductivity (SEC); total and fine bulk density (Table 4.3); and porosity. In total, 21 weather and soil variables were used as input criteria to distinguish turfgrass seeding clusters in the state of Minnesota.

Scatterplots of all weather and soil variables were examined and a correlation matrix was tested with all pairwise comparisons. If a correlation was greater than 0.95, then the variable considered secondary was removed; for instance, temperature and growing degree days were highly correlated, but growing degree days is calculated from temperature, so growing degree days was removed from the analysis. Some correlations between 0.9-0.95 were kept and others were discarded. We did not include soil heavy metal information to avoid less relevant variables, which could lead to false site differentiation (Milligan & Cooper, 1987). We attempted to use soil temperature variables in the cluster analysis, but winter snow removal at some sites and inconsistent logging intervals did not allow for uniform comparison. The final 12 variables that remained to be tested in the cluster analysis were TMAX, TMIN, PRCP, SNOW, SNWD, and LAT for weather variables, and sand, clay, OM, SEC, and total and fine bulk density for soil variables. After all variables were collected, they were scaled and centered using the *scale* function in R for cluster analysis.

A principal components analysis was used to plot weather and soil variables at different research sites using the *rda* function in the vegan package with scaling set to true (Oksanen et al., 2020). An agglomerative hierarchical cluster analysis (Milligan & Cooper, 1987) was applied to identify significant seeding clusters using the *hclust* function with the ward.D2 clustering method (Ward, 1963). This was applied on the results of the distance matrix using the *dist* function in R with the Euclidean method. Both *hclust* and *dist* are in the stats package incorporated into base R (R Core Team, 2021). An additional cluster analysis was tested using only the weather variables to identify how that clustering scenario contrasts with both weather and soil variables. The *NbClust* function in the NbClust package (Charrad et al., 2014) was used to identify the optimal number of clusters with the Hubert (Hubert & Arabie, 1985) and Dindex (Lebart et al., 1995) graphical indices. The optimal number of clusters were validated by examining and comparing the coverage and standard deviation of species monocultures between clusters and research sites.

4.3 RESULTS

4.3.1 Soil physical and chemical characteristics

Research sites differed in soil physical and chemical properties (Table 4.3). Most sites were classified as a sandy clay loam. Grand Rapids contained an average organic matter content of 1.8% and was similar to Bemidji at 2.1%, Duluth at 2.6%, and Chatfield and St. Cloud both at 2.7%. International Falls and Edina contained the most organic matter at 6.6% and 5.8%, respectively. Duluth contained the lowest available K (56 mg kg^{-1}) similar to Grand Rapids, Edina, Roseville, Brainerd, and Bemidji. The saturated paste extract electrical conductivity was the highest for Duluth (1.63 mmhos cm^{-1}), Willmar (1.53 mmhos cm^{-1}), Edina (1.43 mmhos cm^{-1}), and St. Cloud (1.4 mmhos cm^{-1}). Content of Zn (43.3 mg kg^{-1}) and Cu (14.4 mg kg^{-1}) were both greater at the Brainerd site than all other locations, likely due to its proximity to a nearby metal recycling plant: truck traffic from the recycling plant was known to deposit dust along the road, which subsequently accumulated onto the roadside. Grand Rapids contained the highest fine bulk density (1.58 g cm^{-3}) and both Grand Rapids and Duluth contained the two highest total bulk densities at 1.71 g cm^{-3} and 1.61 g cm^{-3}, respectively (Table 4.3).

4.3.2 Weather and climate differences

In general, research sites in the southern part of the state experienced warmer maximum and minimum temperatures (Table 4.4), and generally more growing degree days (Table 4.5). Sites located in southern Minnesota also experienced the potential for more intense sunlight based on the latitude. Rainfall precipitation in 2020 was the highest for Chatfield at 31.3 in (794 mm) and lowest for East Grand Forks with 18.3 in (464 mm). The snowfall precipitation in 2020 was highest at Duluth at 81.3 in (2127 mm), due to lacustrine effects, and lowest for Fergus Falls at 28.6 in (726 mm) (Table 4.4).

The deviation in observed weather for the duration of the experiment and the climate normal (1991-2020) by month for all research sites are shown in Figures 4.2-5. For all sites, one site contained a cooler temperature maximum than normal in 2020, and four contained a cooler temperature minimum than normal (Table 4.6). In 2020, the greatest deviations in average maximum temperature were found in a warmer Fergus Falls (2 ° F; 1.1 ° C) and a cooler Roseville (-0.9; -0.5 ° C) (Table 4.6). Deviation in observed precipitation from climate normals found most sites were drier than normal (Table 4.6). Duluth received less rain than expected in the month of June of -3.7 in (-94 mm), and Grand Rapids observed more rain than normal in Aug. of +5.4 in (+138 mm) (Figure 4.3).

Soil temperature using the SMEC probe was highly variable across the research sites (Figure 4.5). Duluth peaked at a higher temperature than at all other sites with 15 days of maximum soil temperature greater than 104 ° F (40 ° C) (data not shown). Duluth even had greater soil temperature extremes than Worthington, despite Worthington containing a warmer yearly average air temperature (Table 4.4), but Worthington had 53 days of average soil temperature greater than 86 ° F (30 ° C), whereas Duluth had only 38 days above that threshold. The soil temperature at Duluth also exhibited high thermal conductivity with a range of 55.4 ° C in 2020 using the SMEC probe, and in the months of June, July, and Aug. 2020 the average daily soil temperature range fluctuated 28 ° F (15.6 ° C) (Figure 4.5).

4.3.3 Cluster solutions

Correlations between final variables that were used for the cluster analysis are shown in Table 4.7. The principal components analysis plot shows the ordination distribution of the 14 research locations from the 12 weather and soil variables (Figure 4.6). The dendrogram plot shows the results of the hierarchical cluster analysis beginning with 14 distinct clusters (for n number of research sites) to one. Research sites closer to one another are more similar within the same branch (Figure 4.7). The number of significant seeding clusters depends on at what height the tree is "pruned".

The optimum number of clusters for the dendrogram based on the Hubert and Dindex indices was three (Figure 4.8). If only the weather variables were used to cluster the sites, then East Grand Forks and International Falls were found to cluster together as the most similar sites within a branch (data not shown), similar initially to the clustering solution shown in Figure 4.7, but then the next similar site was Duluth in this scenario. Based on the observed species composition at Duluth (Figure 4.14-16), differences exist in individual species and total turfgrass coverage between itself and East Grand Forks and International Falls.

4.3.4 Cluster validation

The mean and standard deviation of species monoculture coverage within a cluster approximately one year after seeding compared to all research sites is shown in Table 4.8. Research sites that were classified as poor soil quality sites contained the lowest average cluster coverage one year after seeding (30%). Total average observed turfgrass coverage at Brainerd, Duluth, Bemidji, and Grand Rapids was 18.5%, 25.4%, 38.8%, and 45.6%, respectively. Brainerd and Duluth additionally had the poorest average turfgrass coverage before the first winter, which was only 7.9% and 23.5%, respectively. The two geographical clusters contained similar total average turfgrass coverage but have differences in the type of coverage. The northern cluster compared to the central/southern cluster had more alkaligrass, less buffalograss, less tall fescue, and relatively similar amounts of hard fescue, Kentucky bluegrass, and slender creeping red fescue (Table 4.8).

Both hard fescue and slender creeping red fescue, the two fine fescue species, were the top performing monoculture species for all clusters. One difference between slender creeping red fescue and hard fescue is that slender had a higher standard deviation for the central/southern cluster compared to hard fescue. Buffalograss coverage was tied for the most abundant species at poor soil quality sites (41%) and within that cluster it was greater than Kentucky bluegrass and tall fescue (Table 4.8). Tall fescue contained the most coverage at research sites classified in the central/southern cluster (74%) and the lowest coverage at the poor soil quality sites (17%), and within the poor soil quality cluster, tall fescue was one of the poorest performers compared to the other monoculture treatments. Tall fescue also had the highest standard deviation compared to the other monoculture species across all research sites. Alkaligrass had the highest average coverage at poor soil quality sites (27%) and at that cluster was the only monoculture species comparable all others. Alkaligrass was also statistically equivalent to buffalograss as the poorest performing monoculture species. Kentucky bluegrass had better coverage at the northern and central/southern cluster than the poor soil quality cluster (Table 4.8).

The standard deviation of an individual monoculture was less for all clusters compared to all research sites except for one instance; in that instance, the standard deviation of alkaligrass was higher at poor soil quality sites (Table 4.8). Based on the reduction in standard deviation for 17 of 18 monoculture species in the three-cluster scenario, our statistical approach has distinguished the unique strengths and weaknesses of different species based on soil and weather differences and shows to be a valid method of clustering. Therefore, we validated that the optimum solution was a three-cluster scenario, with clusters for (1) northern Minnesota, (2) central/southern Minnesota, and (3) sites throughout the state with poor soil characteristics (Figure 4.6).

4.4 DISCUSSION

There are currently only statewide recommended seed mixtures for roadsides in Minnesota; differences in seed mixture components are largely based on roadside aesthetics rather than geographic or edaphic factors (MnDOT, 2014). We gathered 12 variables and clustered sites based on those differences and validated the clustering results by assessing our turfgrass coverage and deviation (Figure 4.9-26; Table 4.8). Based on our cluster analysis results, we recommend three seeding clusters for Minnesota (Figure 4.7-8): two geographic clusters (northern and central/southern), and one cluster based on poor soil characteristics of a site (Figure 4.15-16; 4.24-26; Table 4.8).

4.4.1 Soil characteristics and remediation

Soil characteristics of sites classified within the poor soil quality cluster include high sand and low clay contents, low organic matter, high bulk density, and high saturated paste extract electrical conductivity relative to sites contained within the geographical clusters (Figure 4.6; Table 4.3). A previous roadside research experiment covering multiple states found that an urban site in New Jersey with the poorest coverage contained the highest saturated paste extract electrical conductivity (8.7 mmhos cm^{-1}) (Watkins et al., 2019), and only weeping and seaside alkaligrass (*Puccinellia maritima* (Huds.) Pari.) contained statistically more than 0% coverage at that site two years after seeding. This shows the importance of using specific species for sites with high saturated paste extract electrical conductivity. Hopkinson et al. (2016) evaluated vegetation cover at 29 roadsides and medians in West Virginia and found sites containing less than 50% vegetation cover were associated with poor soil properties. Poor soil properties were defined as containing high saturated paste extract electrical conductivity ranging from 0.36-1.54 mmhos cm^{-1}, or low organic matter content of 1.7% or less. Additionally, Hopkinson et al. (2016) found that soil texture was not a significant factor, and an organic matter content of 2.2% was recommended as sufficient for roadsides. With this organic matter criterion, Grand Rapids and Bemidji, in our study, would have limited vegetation cover potential, assuming a species that was seeded could not tolerate a lower threshold. Vegetation coverage is also more limited when bulk density is greater than 1.7 g cm^{-3} on coarser soils (Daddow, 1983) and this could have limited coverage at Grand Rapids and portions of Duluth. In West Virginia, Hopkinson et al. (2018) tested different roadside mixtures at different elevations and found less total coverage at the high-elevation site, and those findings were attributed to poor soil conditions.

The soil texture can also have a significant impact on coverage. Greater sand content in soils has been found to allow for greater hydraulic conductivity when the soil is frozen (Stoeckeler & Weitzman, 1960). In Minnesota, roadsides are salted in the winter and because roadside soils are usually sandier, then the combination could allow more salt damage. One experiment conducted by Haan et al. (2012) found more sand in the soil resulted in improved overwintering of forbs, but those findings may not be applicable to turfgrass. Baadshaug (1973) found that a sandy loam soil texture was colder by 0.5-1 ° C in the winter than a clay texture. Baadshaug (1973) also found a sandy loam was the second worst texture for spring grass coverage on plots that contained an ice sheet treatment and those that were snow-free. Clay soils resulted in the greatest injury on snow free plots, but the least amount on ice-covered plots, therefore it is important to recognize that winter effects and soil physical factors are complex (Baadshaug, 1973). Recommending a turfgrass seed mixture for specific soil characteristics would not be unusual then with the limitations that are common among roadside soils.

We found lower average coverage for the poor soil quality cluster (Table 4.8) suggesting that there is opportunity for improved species and cultivar recommendations and/or soil remediation. A cost-tradeoff would be helpful to identify if and how much topsoil or compost should be incorporated into a site depending on the current soil conditions. Mixtures could be evaluated in soil containing different levels of remediation, thereby allowing for a non-dichotomous decision. Duell and Schmit (1975) found that amending a roadside site containing 96% sand with 5 cm of silty clay topsoil could improve establishment. In a similar manner, Dunifon et al. (2011) found good turfgrass establishment for one year when applying compost; however, coverage began to decline 1-2 years after seeding in that study, and those findings were attributed to poor subsurface soil conditions, in addition to high compaction. Watkins and Trappe (2017) found no benefits of applying several different amendments along roadsides, but those results could have been limited by the tested sites containing sufficient soil chemical and physical characteristics.

4.4.2 Species and cluster coverage differences

There was evidence of slender creeping red fescue with a larger standard deviation in the central/southern cluster compared to the northern cluster (Table 4.8). We observed 'SeaMist' slender creeping red fescue was less adapted to the warmer regions than 'Gladiator' hard fescue, especially in the middle of the summer and if it was dry, potentially explaining that larger variation. Tall fescue was found to contain the largest standard deviation of all monoculture species showing that in some instances in can be a significant benefit along roadsides and in others, such as in the poor soil quality cluster, in can be of little to no benefit. Tall fescue is known to be susceptible to winter injury in Minnesota along roadsides (Friell et al., 2015) explaining why it may have performed the best in the warmer areas of the state (Table 4.4; Table 4.8) and ones with warmer winter soil temperature (Figure 4.5). Duluth was likely heavily affected by soil properties compared to weather variables and illustrates the importance of clustering by both soil and weather variables. With weather variables alone, the clustering of Duluth with East Grand Forks and International Falls would not be appropriate since species and total coverage was much different (Figure 4.14-16).

4.4.3 Research site management

Total amount and type of coverage can also be impacted by the management of research sites. We observed cooler winter minimum soil temperature at sites that had aboveground snowfall cleared in the winter months (Chatfield, Duluth, Bemidji, Brainerd, Roseville, and possibly more) (Figure 4.5). Sites with natural snow cover tended to have more turfgrass coverage the following spring, and this could be due to soil temperatures hovering around 0 ° C, especially at Marshall and Edina (Figure 4.5). This indicates the need to, when possible, maintain some snow cover on recently seeded roadside vegetation. This reflects similar findings in a grass survival experiment conducted by Baadshaug (1973). Bemidji also experienced lower coverage due to direct winter snowplow damage in addition to the indirect winter effects from less snow cover. Other factors such as the mowing height and frequency could also alter soil temperature, which could influence the amount of light that reaches the surface. Collectively, this shows that soil temperature is a dynamic variable not only influenced by the climate and edaphic factors of the area, but also by management factors dictating its peaks and variation in a single day to an entire season.

4.4.4 Limitations

In our research site selection, stretches of roadsides that are difficult to maintain vegetation may be over-represented because we allowed a few cities to choose the areas. Site selection shows some limitations based on the results of our principal components analysis plot (Figure 4.6). We are lacking sites containing both high clay content and high bulk density, because root limitations are significant at 1.4 g cm^{-3} or greater for clay soils (Daddow, 1983). We are also lacking a site located in southwest Minnesota (Figure 2.1) containing soil properties similar to sites classified within the poor soil quality cluster. Maintaining similar mowing within a couple sites and across all sites was also difficult and this could have affected species performance disproportionately (see Table 2.6 for maintenance details). Data collection only occurred in the fall and in the spring each year and differences were observed in species coverage especially in the middle of the growing season at some sites. Interesting images of soil, weather, and turfgrass coverage from some roadside research sites are shown in Figure 4.27-31.

4.4.5 Conclusion

Based on data collected from 14 research sites, we have identified three different turfgrass seeding clusters for Minnesota. One cluster was designated for poor soil quality sites and two are geographical clusters. Future research should focus on precisely defining a poor soil quality site, and the regional clusters could be expanded, refined, or modified. Future turfgrass mixture testing in Minnesota will need to consider the trend of climate change. Species and mixtures should be recommended that are tolerant of current and future conditions. Continued consideration should be given to identify species and cultivars that are adapted to roadsides and the cluster of interest. Germplasm could be collected along roadsides and tested in the respective cluster for adaptability. Together, this will continue to create headway to improve the establishment and persistence of turfgrasses over time along Minnesota roadways. This will reduce erosion and visibility impairments and maintain a safer roadway.

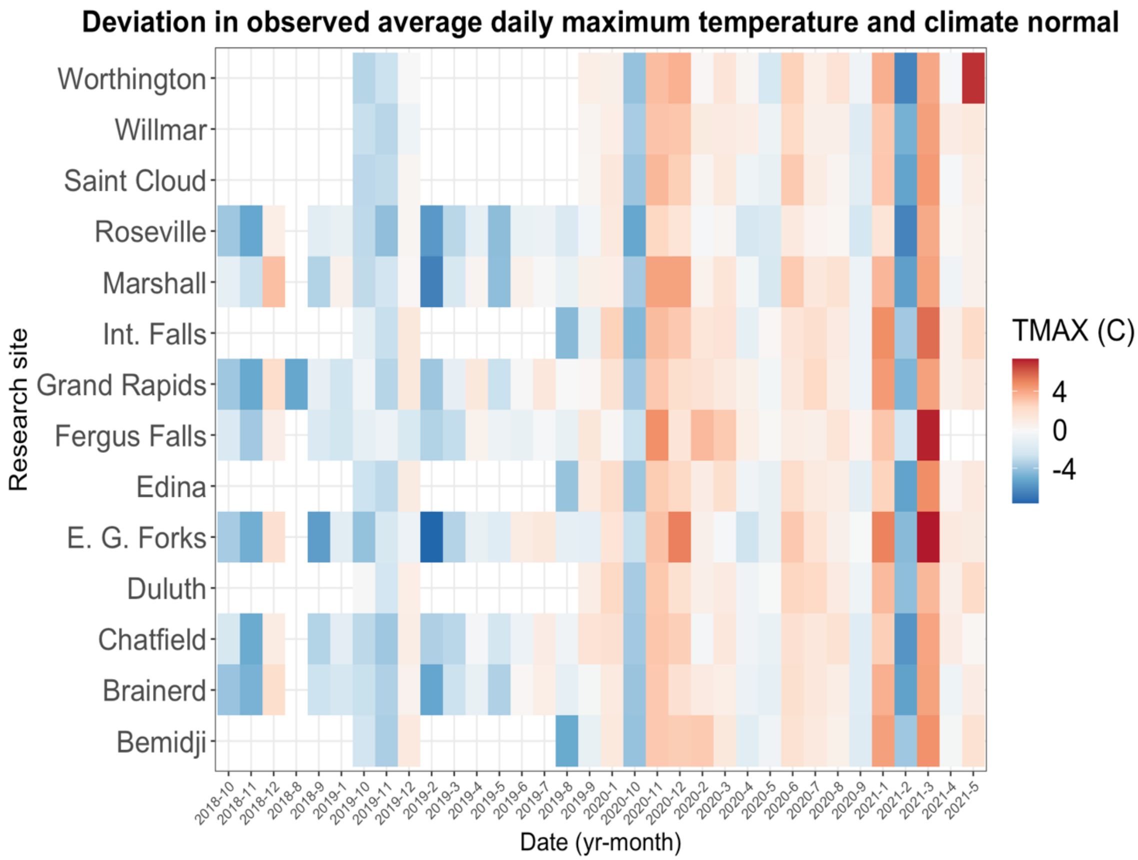

Figure 4.1 Monthly climate normal (1991-2020) temperature maximum data subtracted by observed monthly average. Redder indicates a location was warmer than normal and bluer indicates it was cooler than normal. TMAX = maximum temperature.

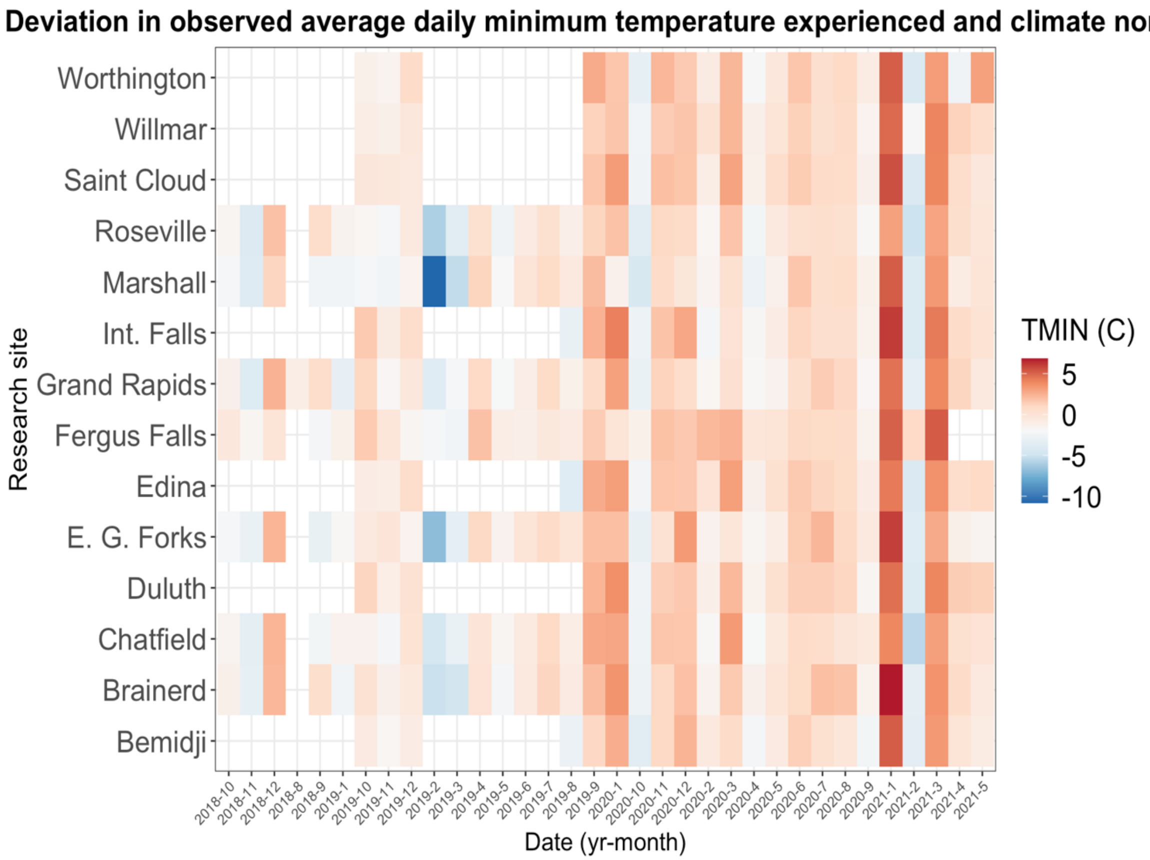

Figure 4.2 Monthly climate normal (1991-2020) temperature minimum data subtracted by observed monthly average. Redder indicates a location was warmer than normal and bluer indicates it was cooler than normal. TMIN = minimum temperature.

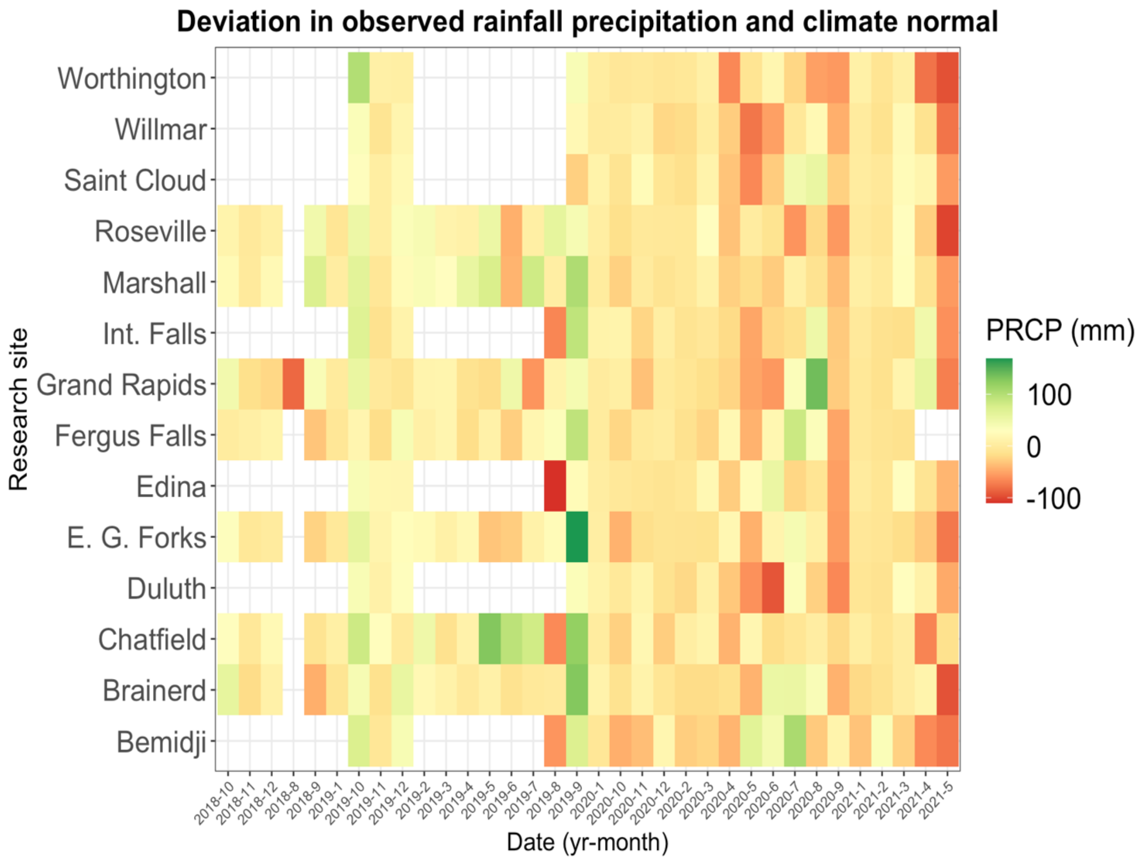

Figure 4.3 Monthly climate normal (1991-2020) rainfall precipitation data subtracted by experienced monthly average. Redder indicates a location was drier than normal and green indicates it was wetter than normal. PRCP = rainfall precipitation.

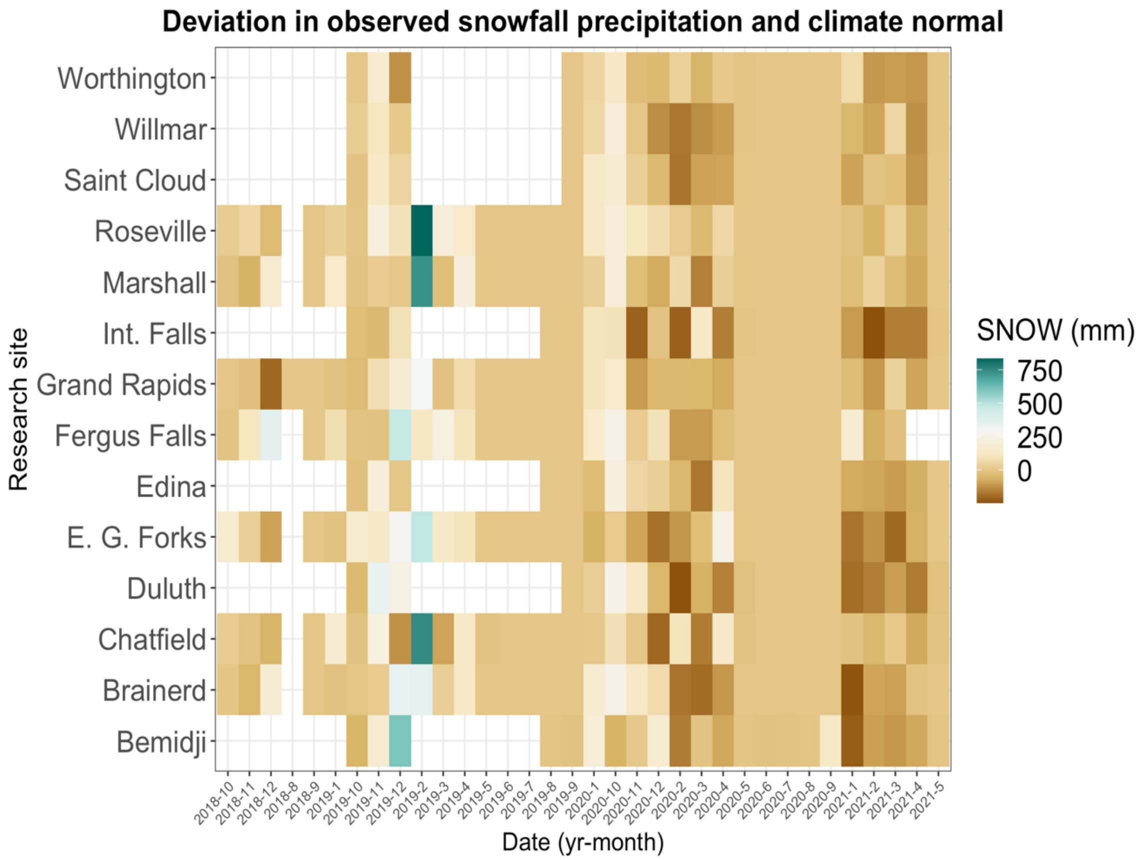

Figure 4.4 Monthly climate normal (1991-2020) snowfall precipitation data subtracted by experienced monthly average. Browner indicates a location had less snowfall than normal and greener indicates a location had more snow than normal in that month. SNOW = snowfall precipitation.

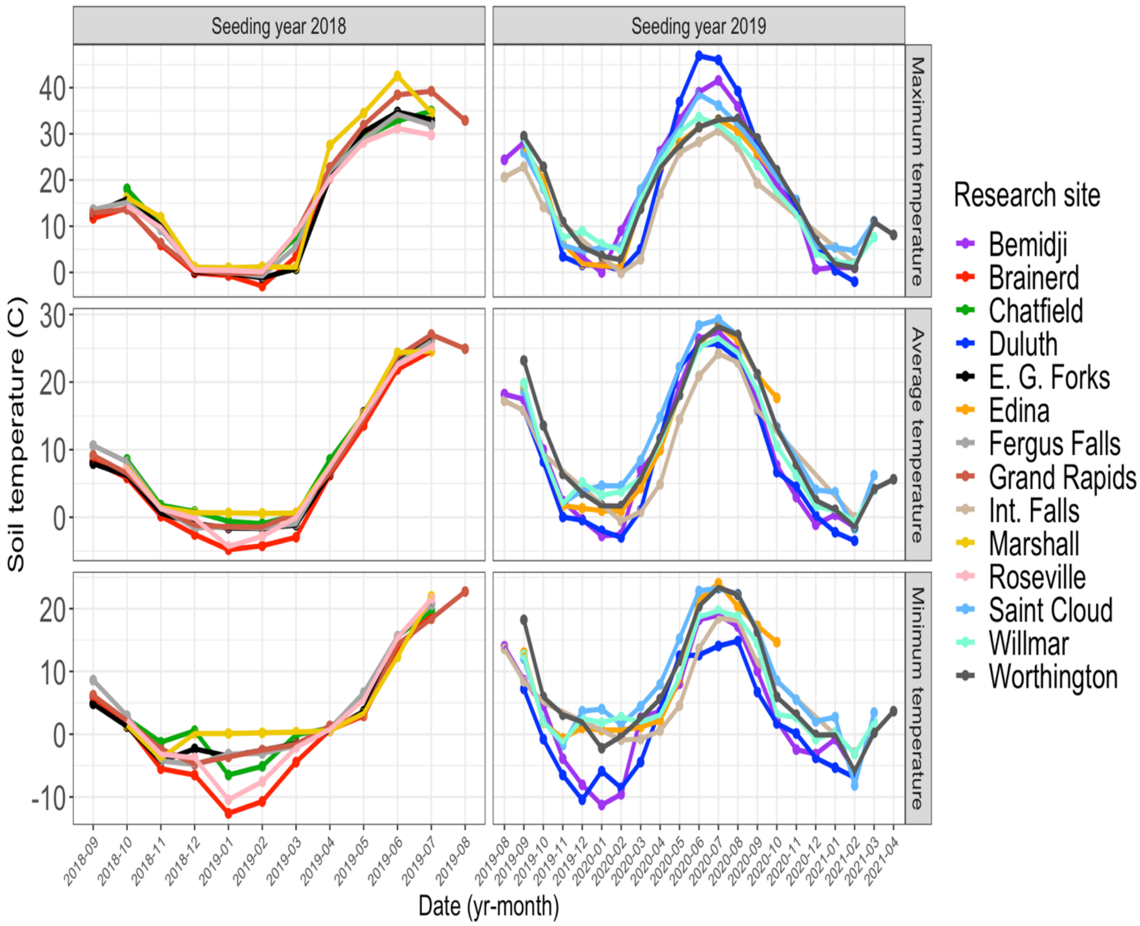

Figure 4.5 Average monthly soil temperature using the SMEC probe. All data was recorded every thirty-minutes. International Falls is missing data from Oct. 18, 2019 to Feb. 12, 2020 and Sep. 14, 2020 to Feb. 15, 2021, since temperatures of close to -40 ° C caused loggers to malfunction. Duluth is missing data from Mar. 6-May 21, 2019. Edina SMEC probe failed to record data beginning on Oct. 13, 2020.

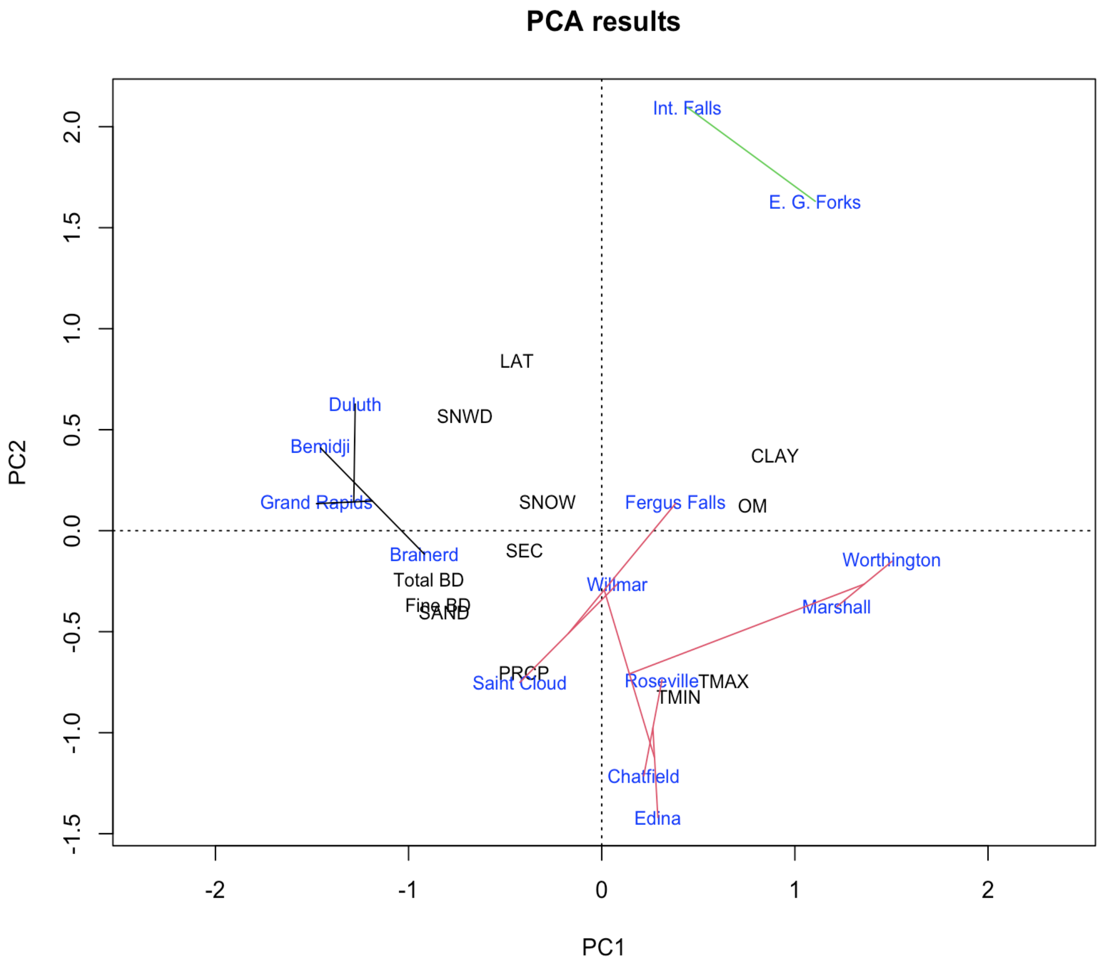

Figure 4.6 Plot of the results of the principal component analysis (PCA). A three cluster dendrogram overlay connects selected sites. LAT = latitude, SNWD = snow depth, SNOW = snowfall precipitation, SEC = saturated paste extract electrical conductivity, OM = organic matter content, BD = bulk density, PRCP = rainfall precipitation, TMAX = temperature maximum, TMIN = temperature minimum. Principal components plot was plotted with scaling set to true.

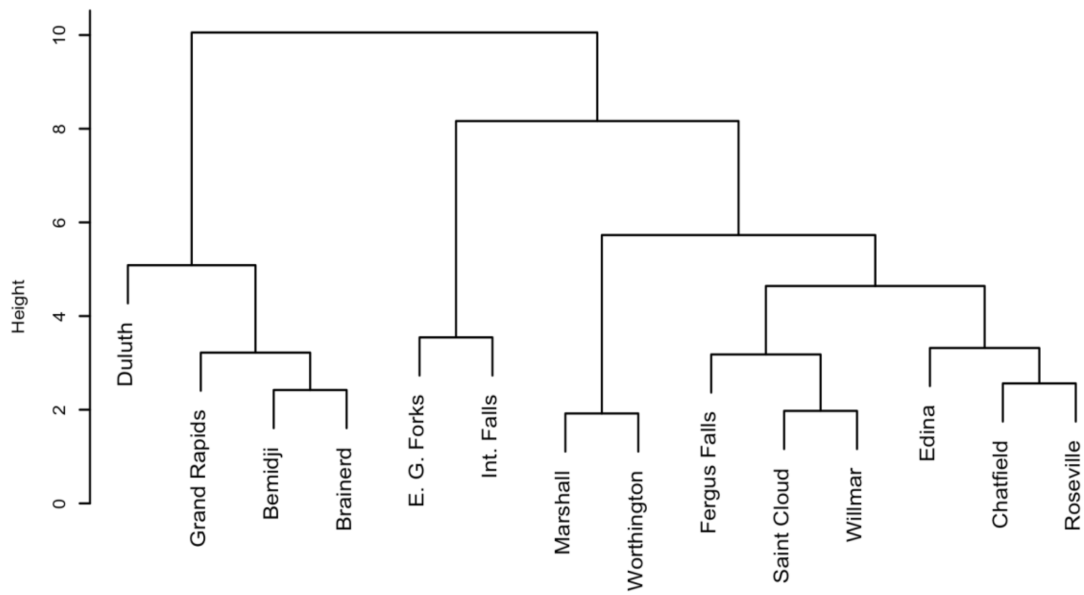

Figure 4.7 Hierarchical agglomerative cluster dendrogram plot. Clustering is based on 12 weather and soil variables. Beginning with 14 research sites (at the bottom), the sites most similar group together, and additional branches within a branch are most similar. The number of significant seeding clusters depends on at what height the tree is pruned.

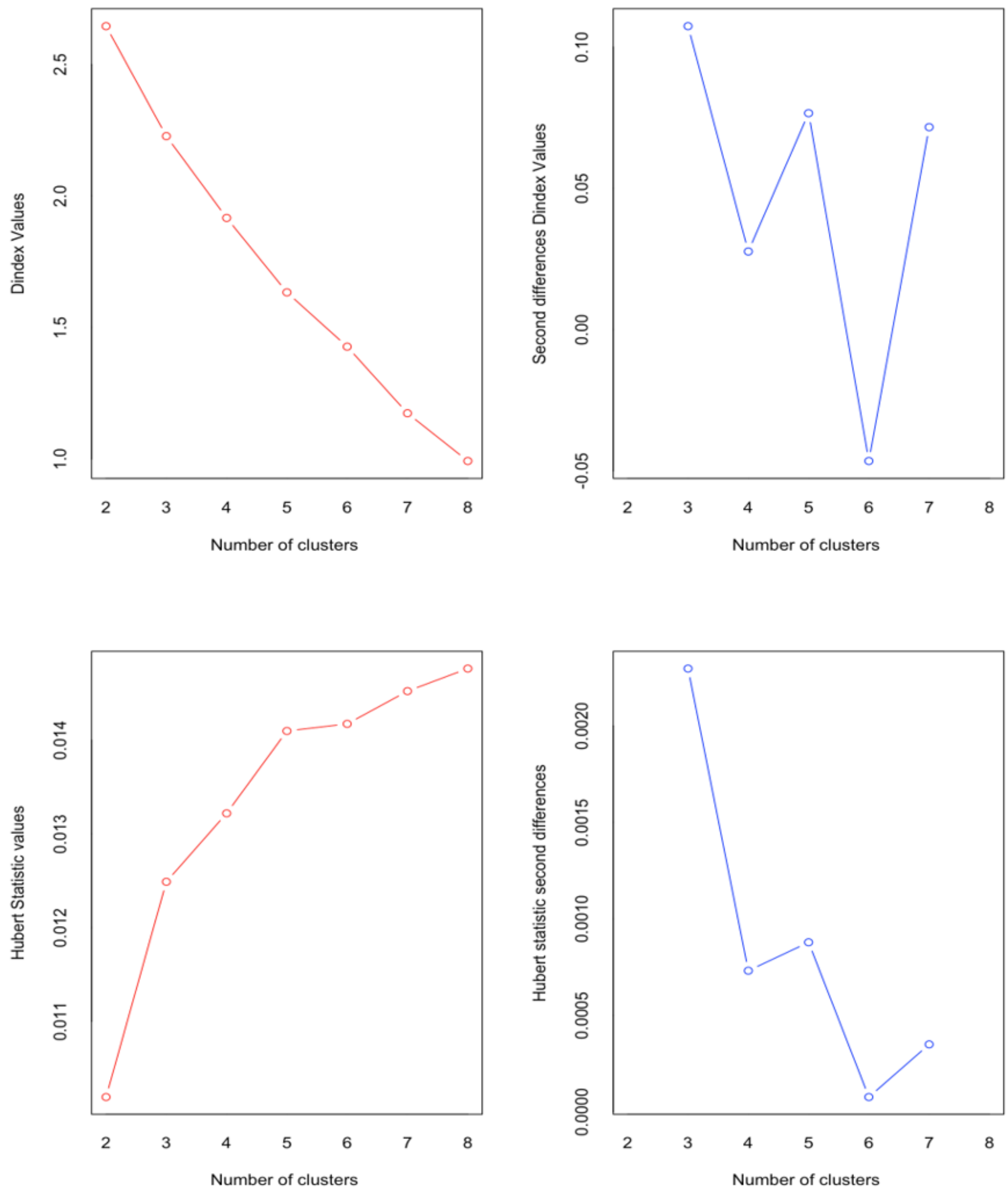

Figure 4.8 Graphical plots of Dindex and Hubert's optimum clustering selection. The peak in the second difference plot shows the optimal number of seeding clusters. Both statistical approaches identify three clusters.

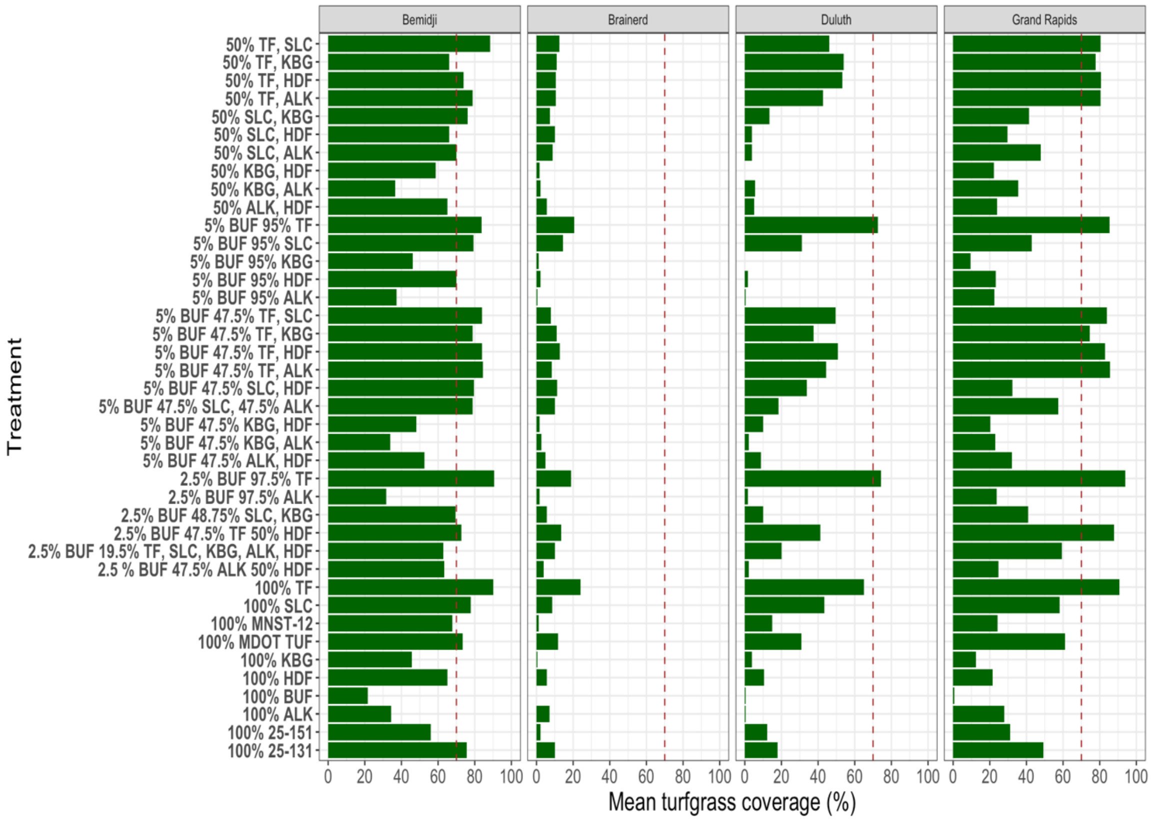

Figure 4.9 Turfgrass coverage sampling for poor soil quality cluster sampled the first fall. Grand Rapids and Brainerd sampled in fall 2018, and Bemidji and Duluth sampled in fall 2019. Brainerd had poor establishment likely due to the site being the only one irrigated by a water truck, instead of the modular drip irrigation system and it contains the highest sand content at 71% (Table 4.3). The brown dashed line is at 70% coverage and allows the viewer to quickly compare treatments between sites. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

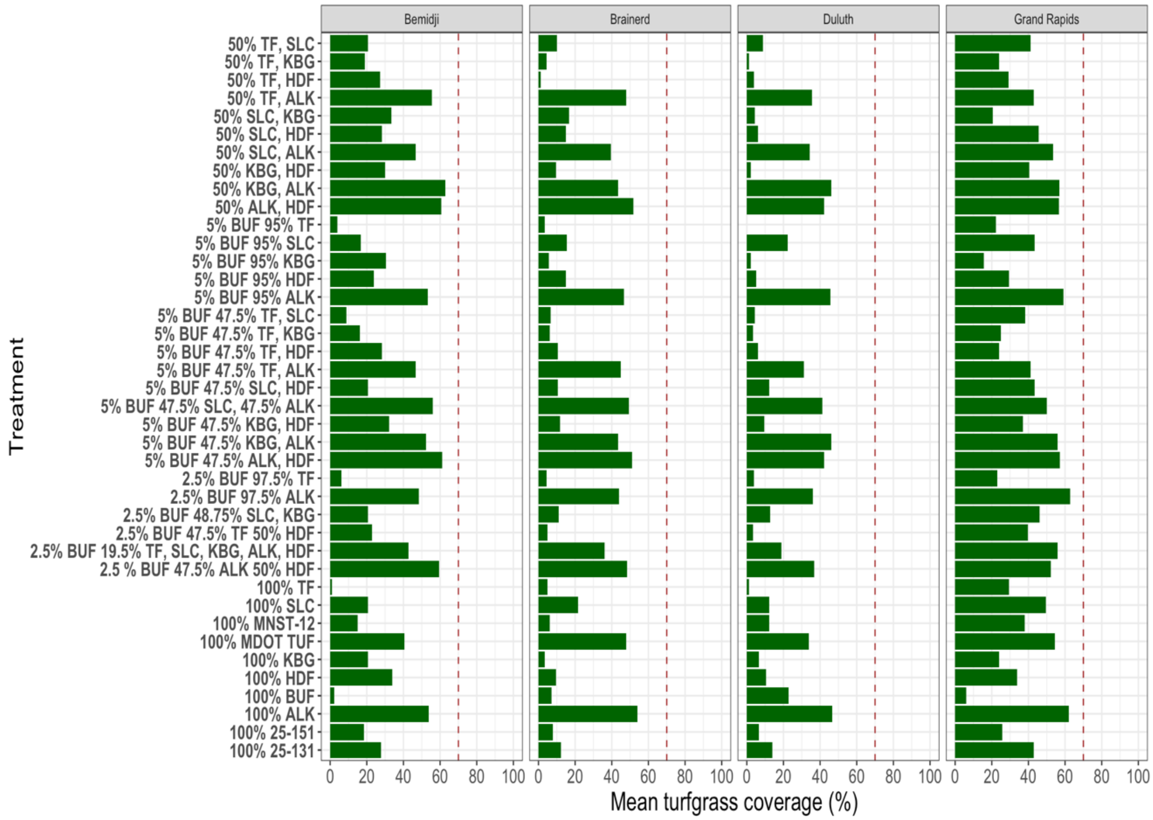

Figure 4.10 Turfgrass coverage sampling for poor soil quality cluster sampled in the spring after the first fall. Grand Rapids and Brainerd sampled in spring 2019, and Bemidji and Duluth sampled in spring 2020. Some plots at Bemidji, especially within blocks one and two were significantly impacted by direct plow damage in plots reducing coverage by approximately 5-20% and indirect effects from extremely cold temperatures (Figure 4.5), so greater standard deviation can be expected in treatment coverage at that location.TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

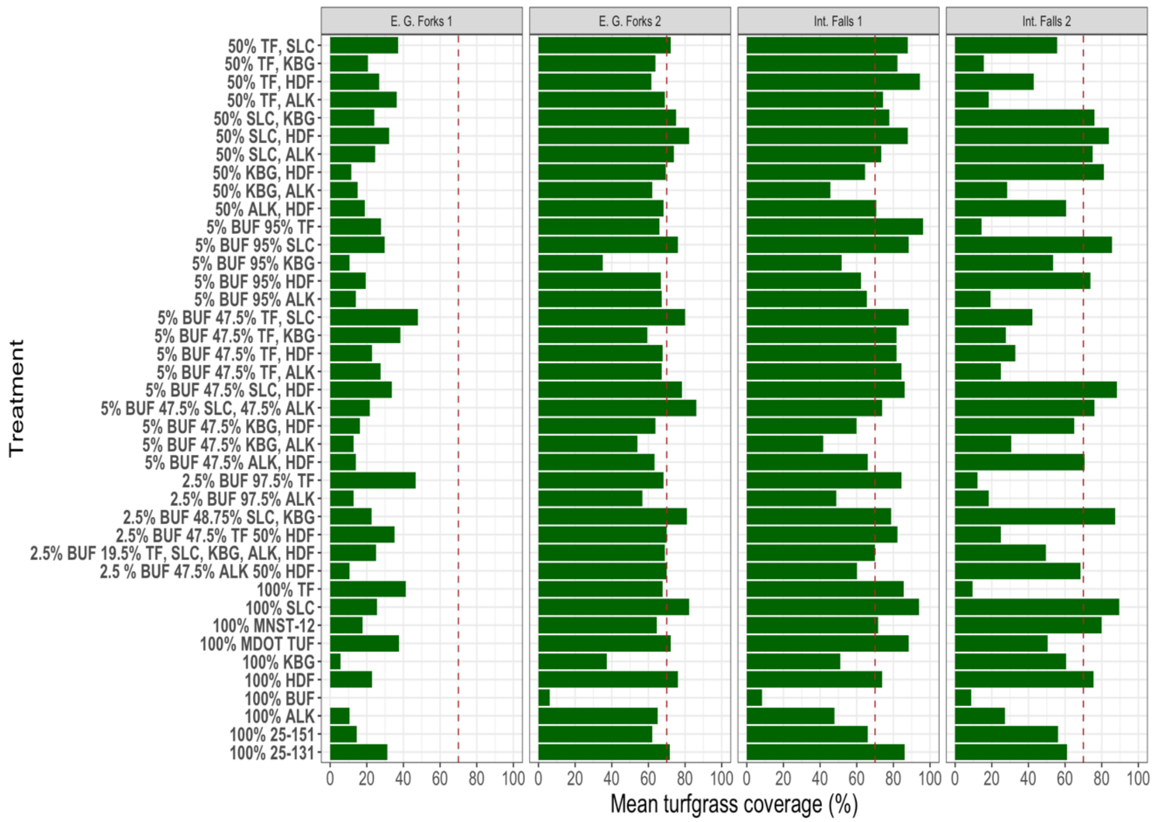

Figure 4.11 Turfgrass coverage sampling for first fall (1) and spring (2) with the sites clustered in the north. East Grand Forks was sampled in fall 2018 (1) and spring 2019 (2). International Falls was sampled in fall 2019 (1) and then spring 2020 (2). East Grand Forks had the lowest growing degree days prior to the first freeze after seeding in the fall of 2018 (233 and 41, base 0 ° C and 10 ° C, respectively (data not showing)); this may explain its low coverage going into the first winter. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

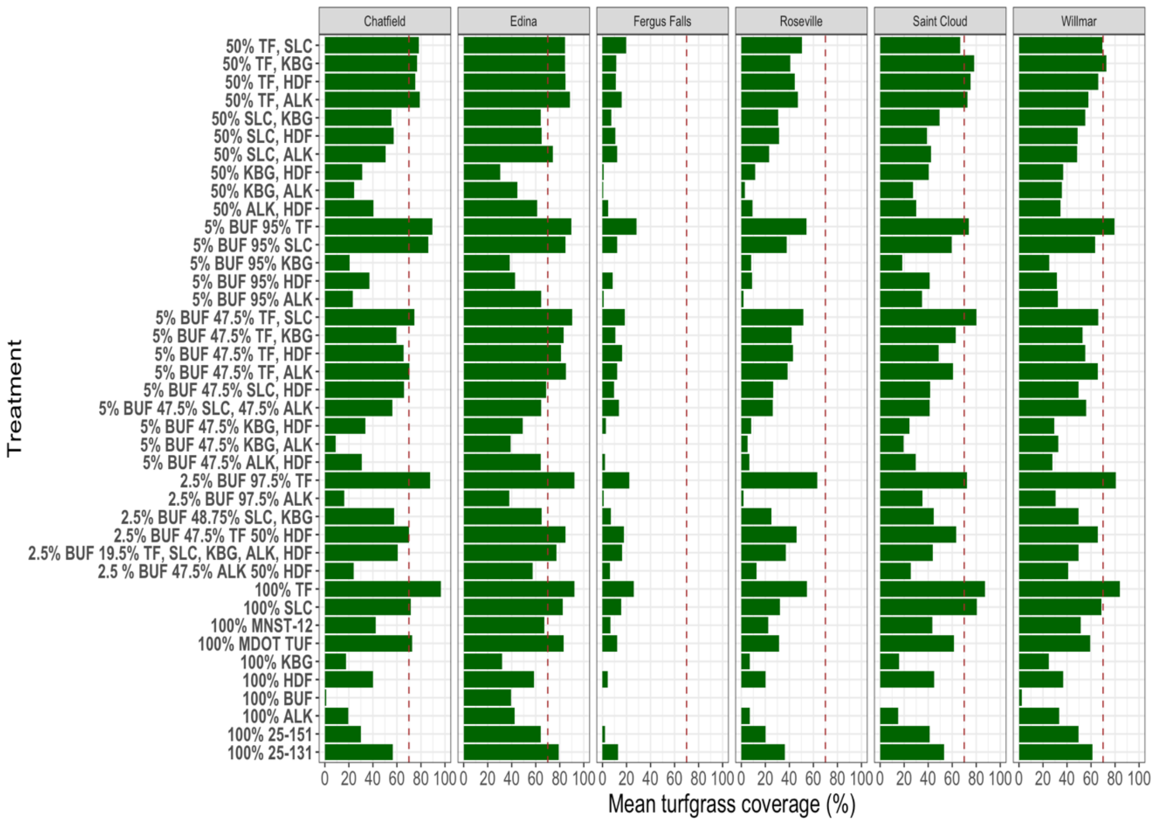

Figure 4.12 Turfgrass coverage sampling in the first fall for the seeding cluster located in central to southeast Minnesota. Fergus Falls had the second fewest total growing degree days in fall 2018 before winter with 348 and 63 base 0 ° C and 10 ° C, respectively, and was sampled that fall with even lower growing degree days of 273 and 63, base 0 ° C and 10 ° C, respectively (data not shown). TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

Figure 4.13 Turfgrass coverage sampling in the first spring after fall for the seeding cluster located in central to southeast Minnesota. Snow was known to be cleared from Chatfield and Roseville in the first winter, and this indirect affect was observed to cause significant damage to tall fescue coverage at Roseville. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

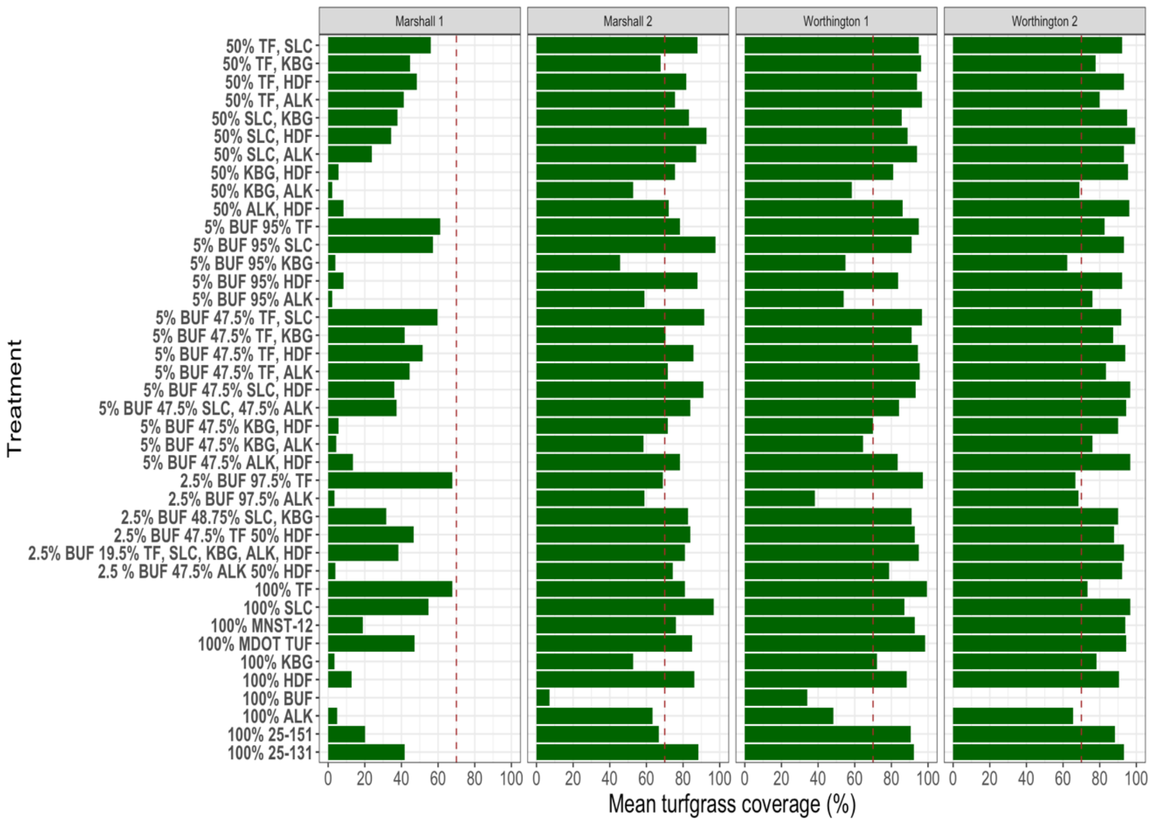

Figure 4.14 Turfgrass coverage sampling in the first fall (1) and spring (2) for the seeding cluster located in southwest Minnesota. Marshall was sampled in fall 2018 (1) and spring 2019 (2). Worthington was sampled in fall 2019 (1) and in spring 2020 (2). Marshall experienced less growing degree days (483 and 79 base 0 ° C and 10 ° C, respectively) than Worthington, which received the second most of all research sites (733 and 241 base 0 ° C and 10 ° C, respectively), prior to winter (Table 4.5). TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss. This cluster was plotted separately due to plot size limitations.

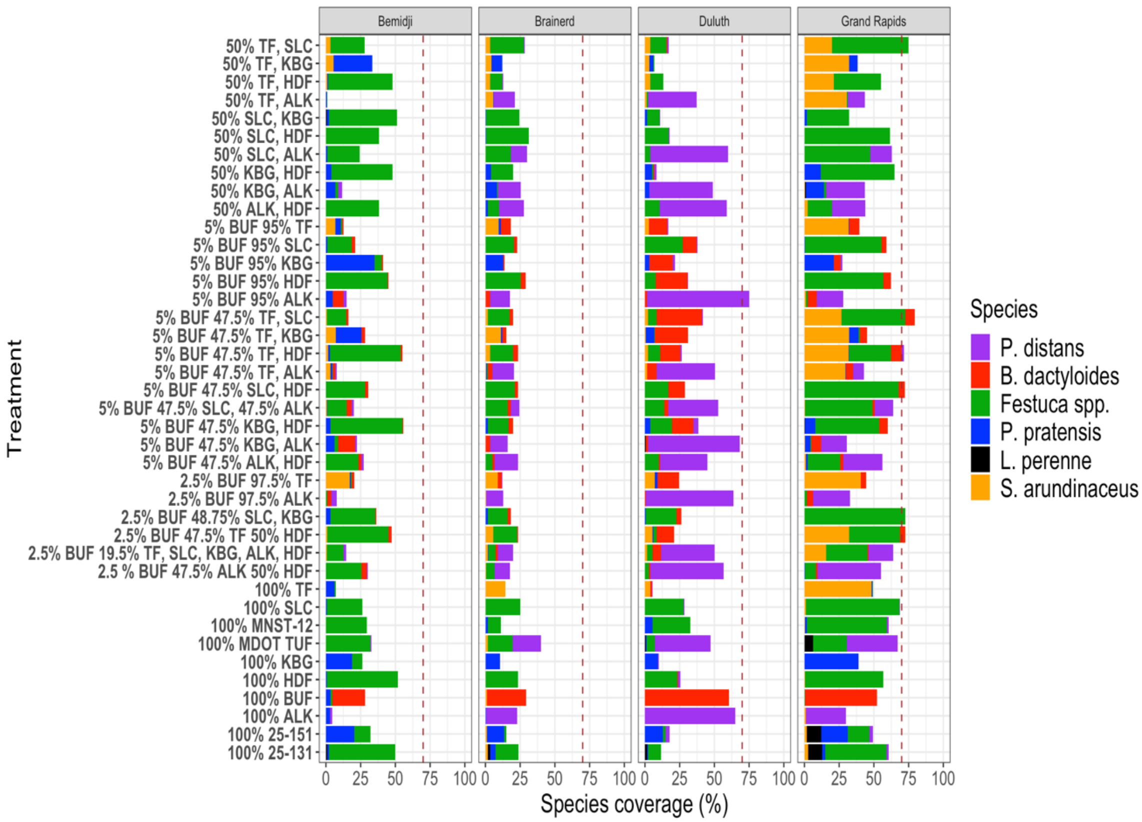

Figure 4.15 Turfgrass species composition coverage sampling for sites classified within the poor soil quality cluster sampled in the fall approximately one year after seeding. Grand Rapids and Brainerd were sampled in fall 2019, and Bemidji and Duluth were sampled in fall 2020. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

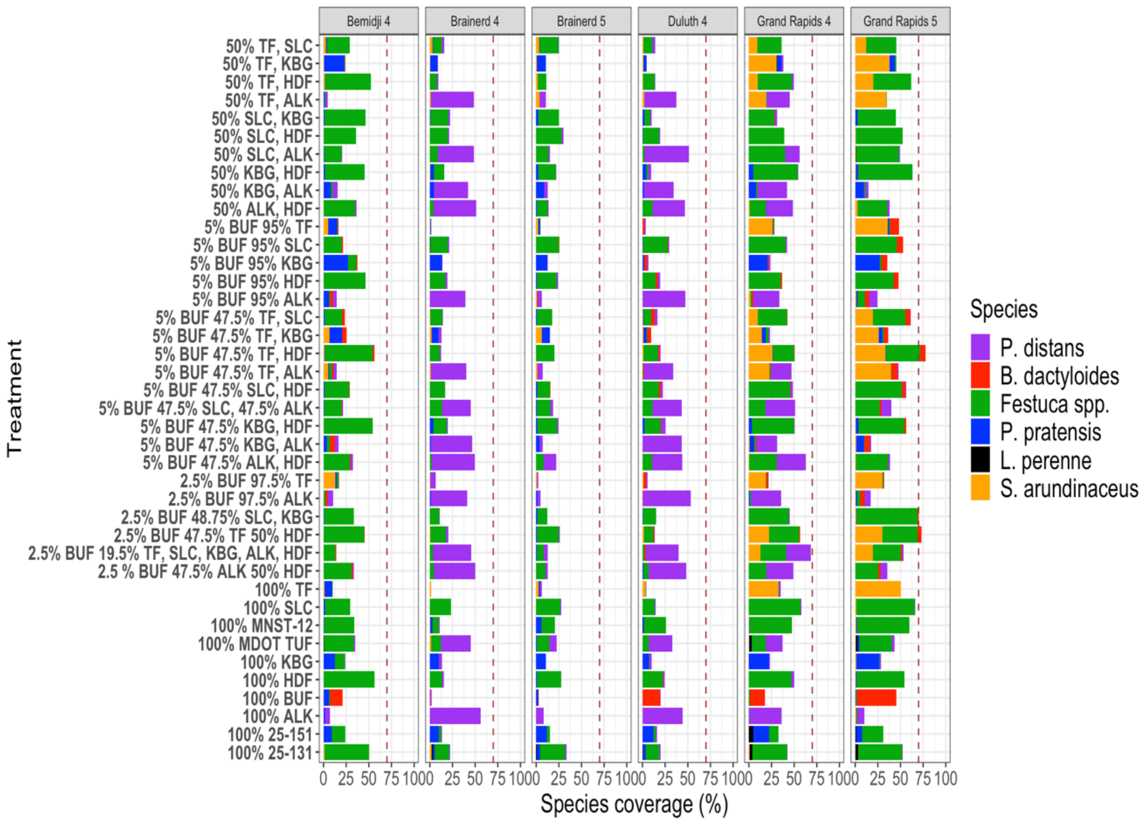

Figure 4.16 Turfgrass species composition coverage sampling for sites classified within the poor soil quality cluster sampled in the spring (4) and fall (5) approximately one and a half and two years after seeding, respectively. Grand Rapids and Brainerd were sampled in spring 2020 (4) and fall 2020 (5), and Bemidji and Duluth were sampled in spring 2021 (4). TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

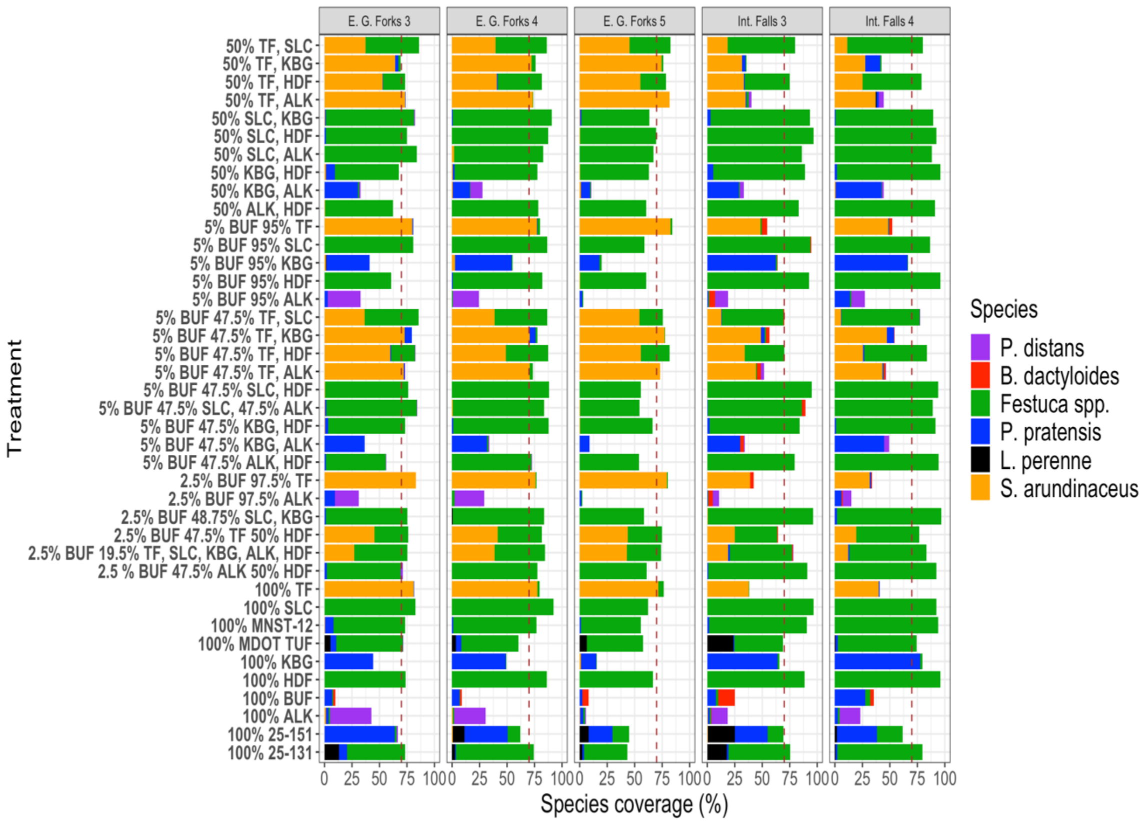

Figure 4.17 Turfgrass species composition sampling for sites within the northern geographical cluster. The third sample time was in the fall approximately one-year after seeding. The fourth was in the spring approximately one and a half years after seeding. The fifth sampling time corresponded to approximately two-years after seeding. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

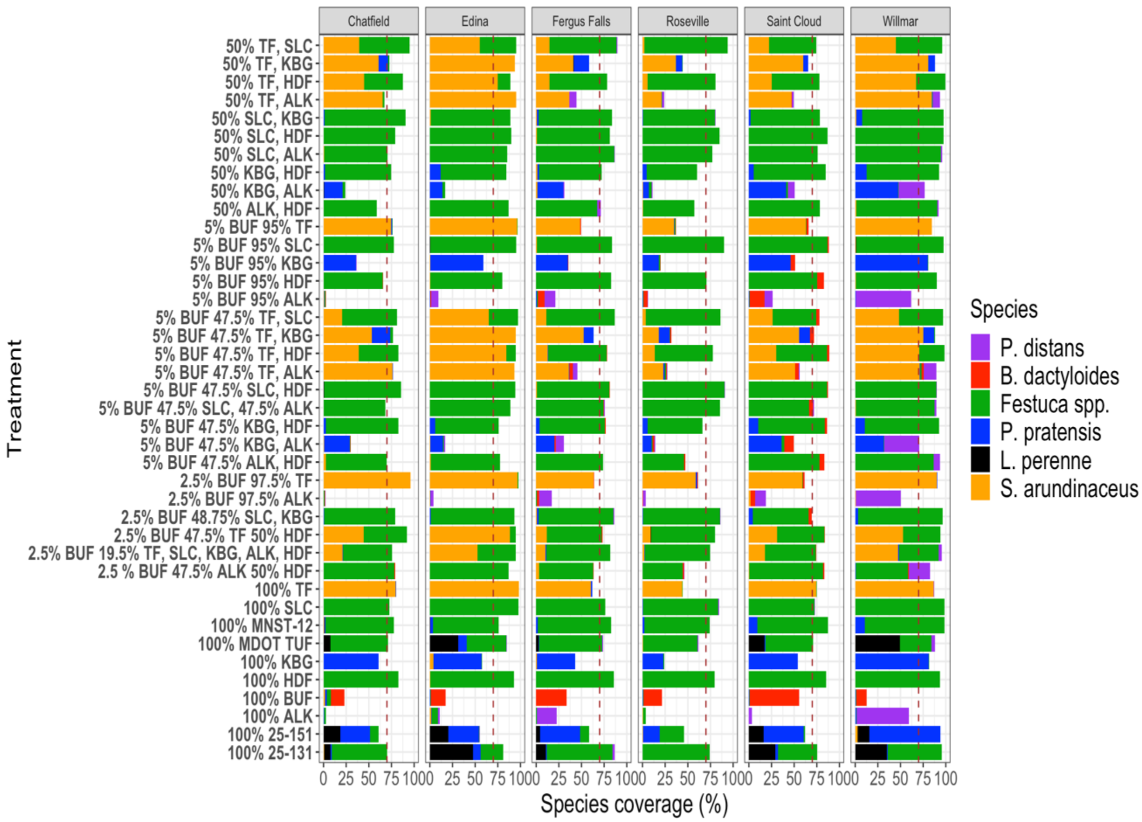

Figure 4.18 Turfgrass species composition coverage sampling at the third sampling time, approximately one-year after seeding. These sites are contained within the seeding cluster located in central to southeast Minnesota. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

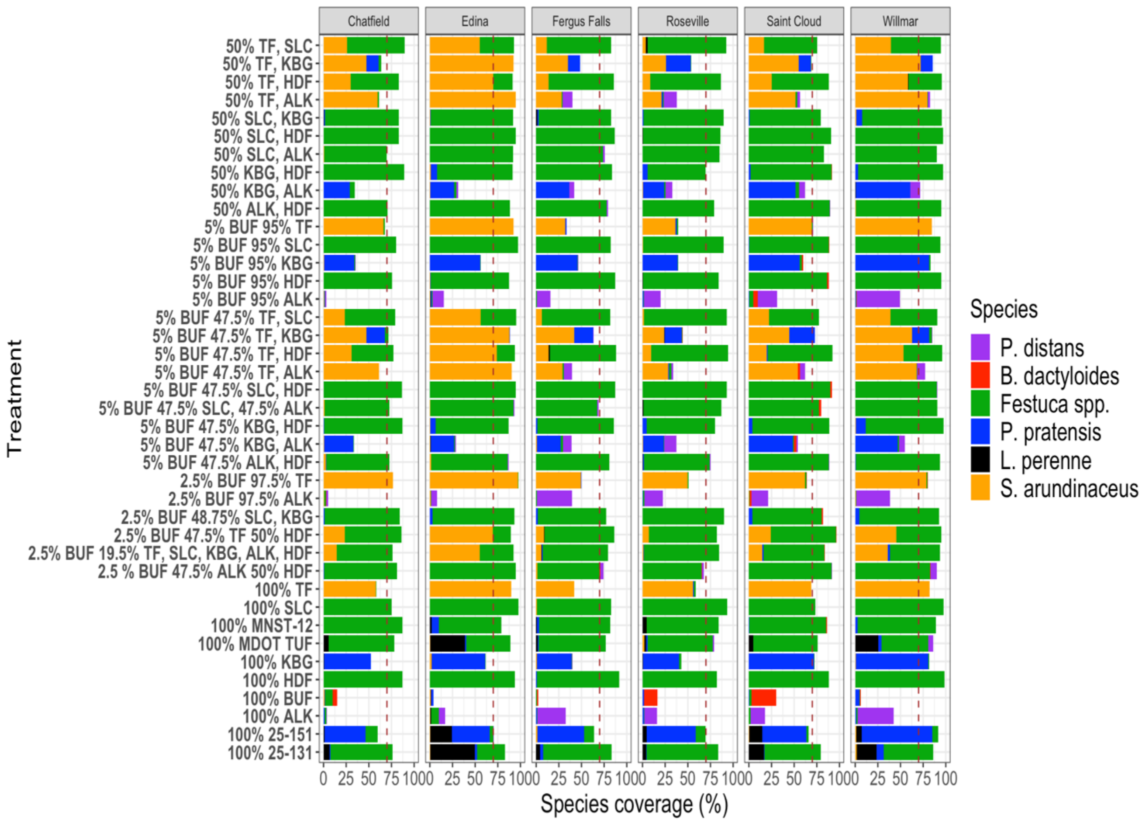

Figure 4.19 Turfgrass species composition coverage sampling at the fourth sampling time at the seeding cluster with sites located in central to southeast Minnesota. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

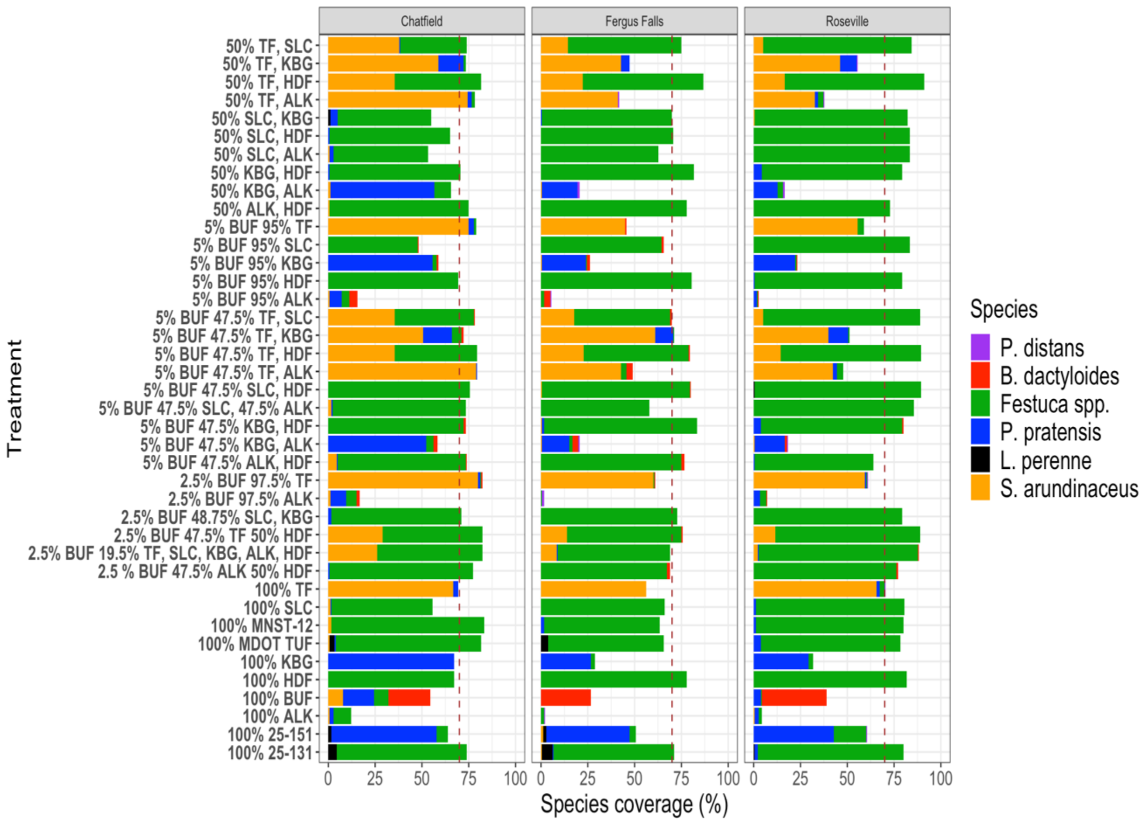

Figure 4.20 Turfgrass species composition coverage sampling at the fifth sample time for the seeding cluster with sites located in central to southeast Minnesota. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss.

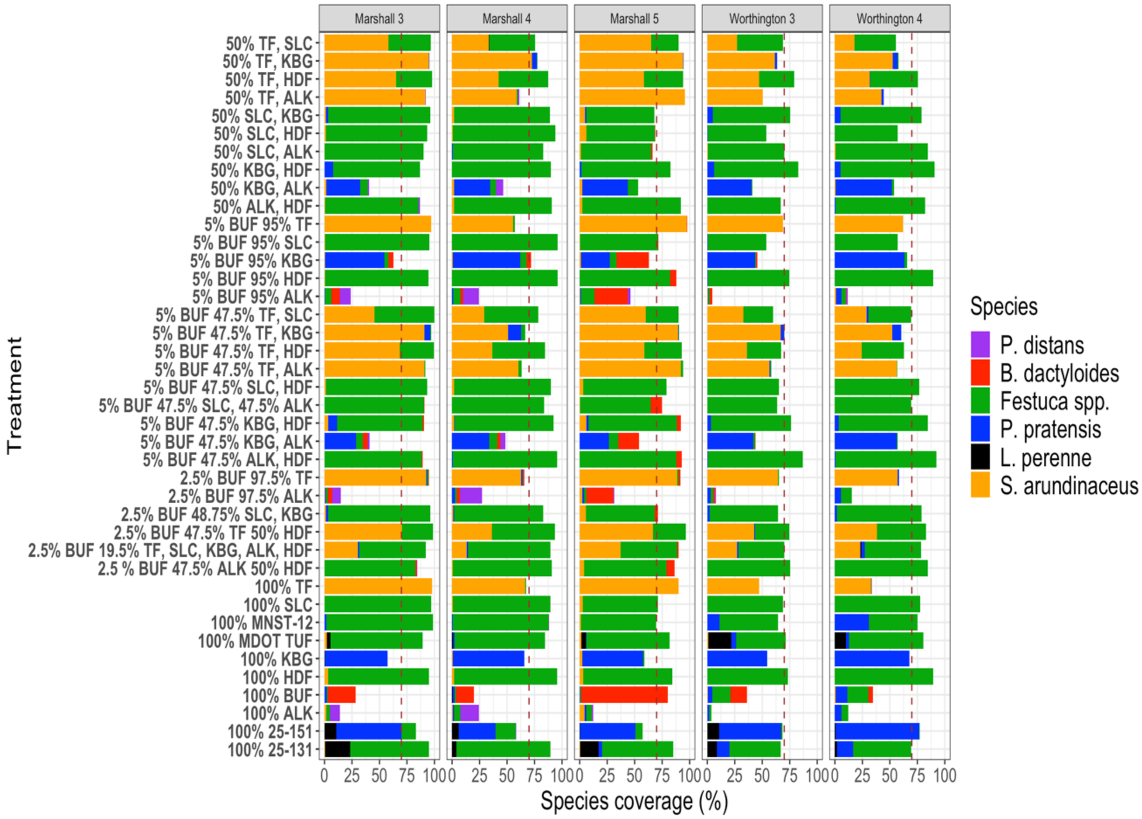

Figure 4.21 Turfgrass species composition coverage for the seeding cluster located in southwest Minnesota. Sampling shows the third, fourth, and fifth sampling dates. The third sample time was in the fall approximately one-year after seeding. The fourth was in the spring approximately one and a half years after seeding. The fifth sampling time corresponded to approximately two-years after seeding. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss. This cluster was plotted separately due to plot size limitations.

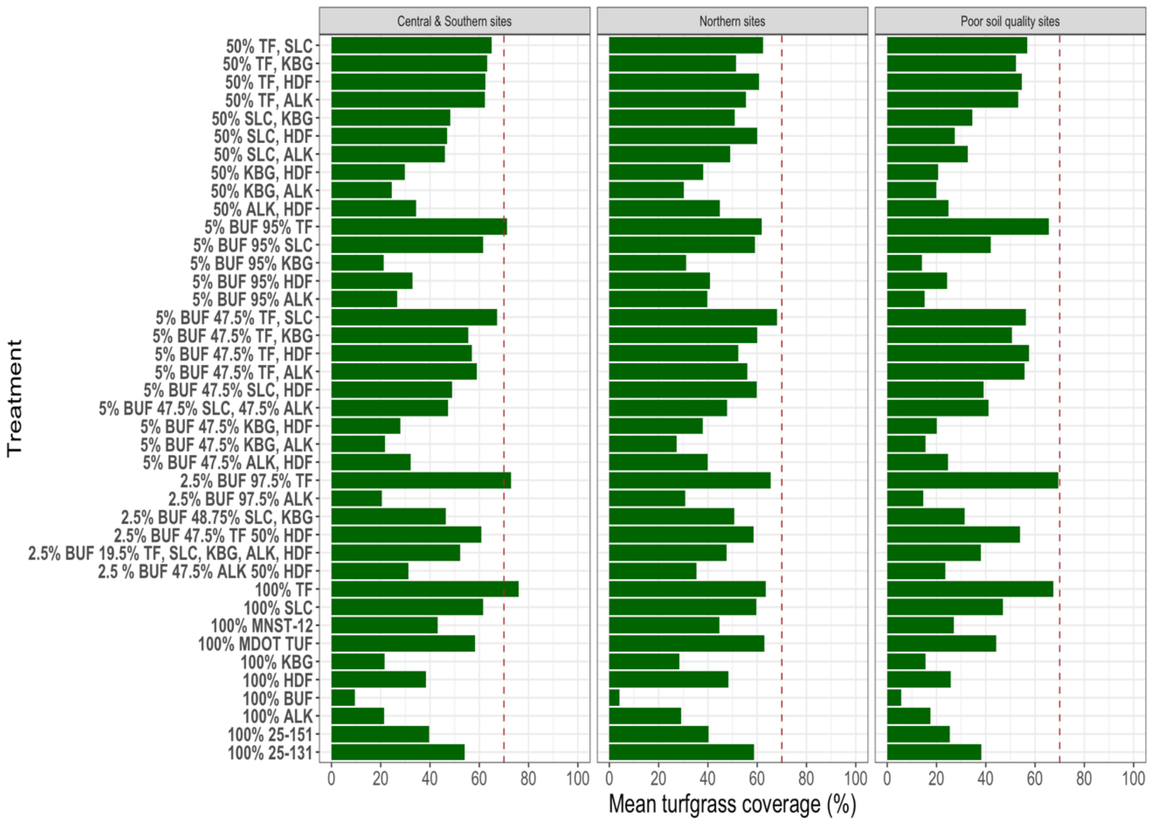

Figure 4.22 Average turfgrass coverage for the three clusters in the first fall sampling time before winter. Northern sites are represented by East Grand Forks and International Falls. Poor soil quality sites contain: Bemidji, Brainerd, Duluth, and Grand Rapids. Central/southern sites include Chatfield, Edina, Fergus Falls, Marshall, Roseville, St. Cloud, Willmar, and Worthington. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss. This figure is intended for a quick comparison between the three clusters since its biological interpretation is reduced due to averaging.

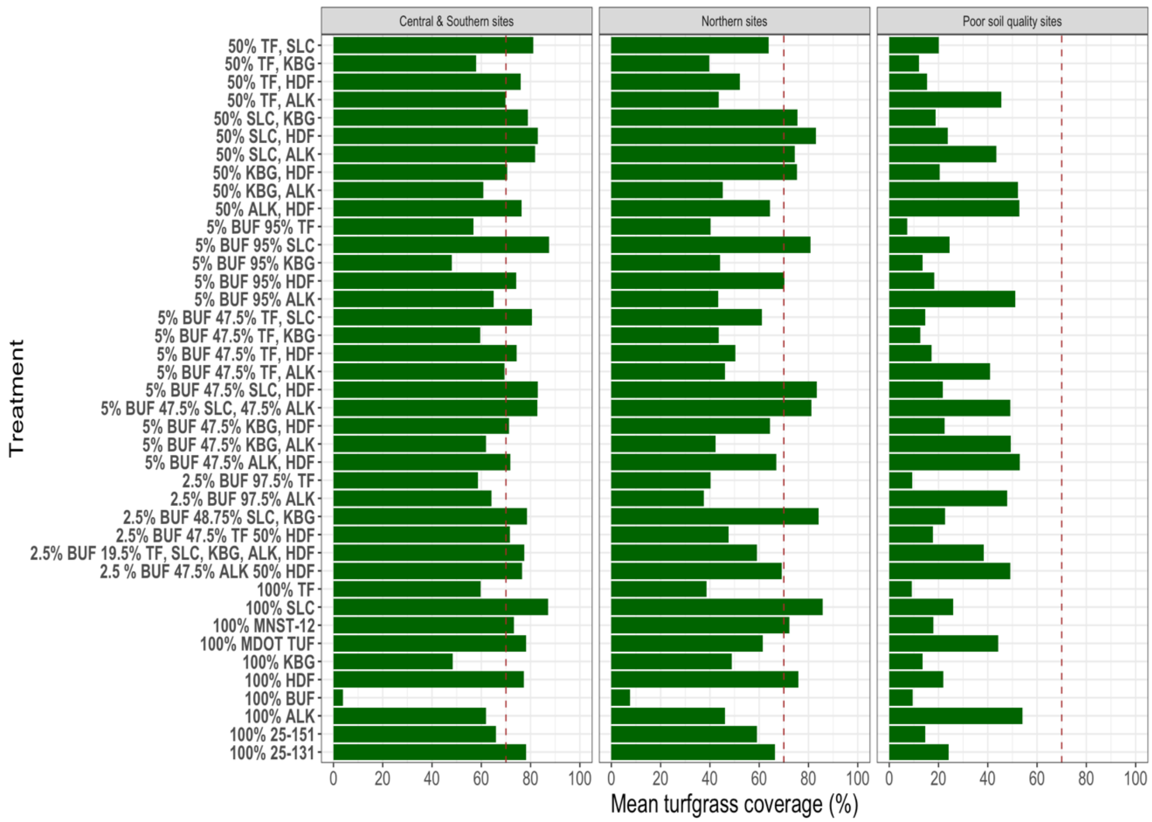

Figure 4.23 Average turfgrass coverage for the three clusters in the second sampling time after the first winter. Northern sites are represented by East Grand Forks and International Falls. Poor soil quality sites contain: Bemidji, Brainerd, Duluth, and Grand Rapids. Central/southern sites include Chatfield, Edina, Fergus Falls, Marshall, Roseville, St. Cloud, Willmar, and Worthington. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss. This figure is intended for a quick comparison between the three clusters since its biological interpretation is reduced due to averaging.

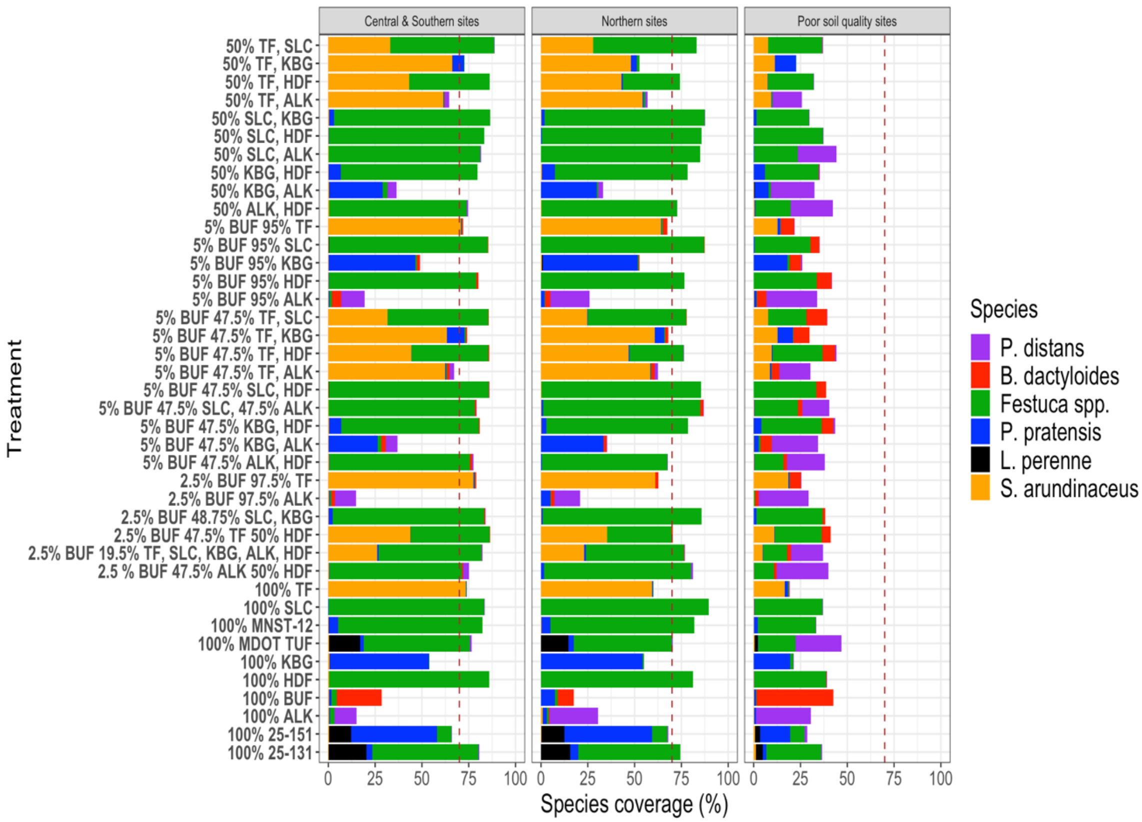

Figure 4.24 Average species composition for the three clusters in the third sampling time approximately one year after seeding. Northern sites are represented by East Grand Forks and International Falls. Poor soil quality sites contain: Bemidji, Brainerd, Duluth, and Grand Rapids. Central/southern sites include Chatfield, Edina, Fergus Falls, Marshall, Roseville, St. Cloud, Willmar, and Worthington. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss. This figure is intended for a quick comparison between the three clusters since its biological interpretation is reduced due to averaging.

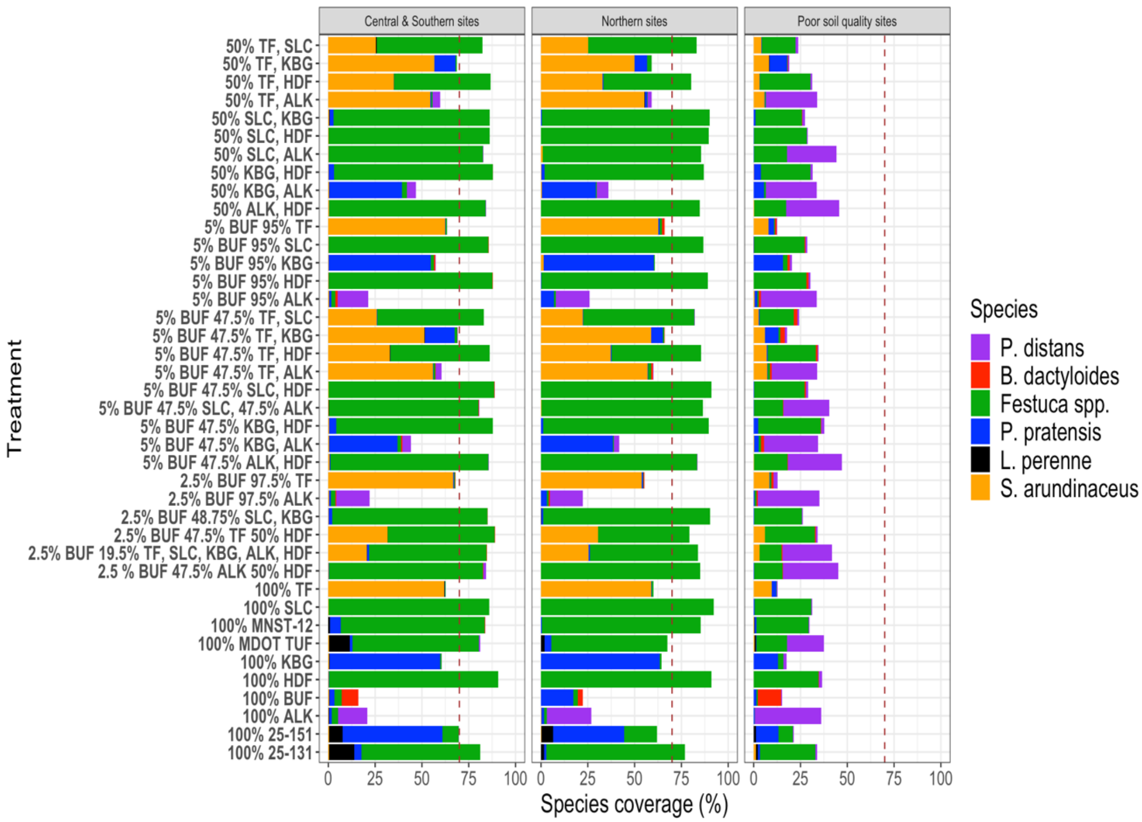

Figure 4.25 Average species composition for the three clusters in the fourth sampling time approximately one and half years after seeding. Northern sites are represented by East Grand Forks and International Falls. Poor soil quality sites contain: Bemidji, Brainerd, Duluth, and Grand Rapids. Central/southern sites include Chatfield, Edina, Fergus Falls, Marshall, Roseville, St. Cloud, Willmar, and Worthington. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss. This figure is intended for a quick comparison between the three clusters since its biological interpretation is reduced due to averaging.

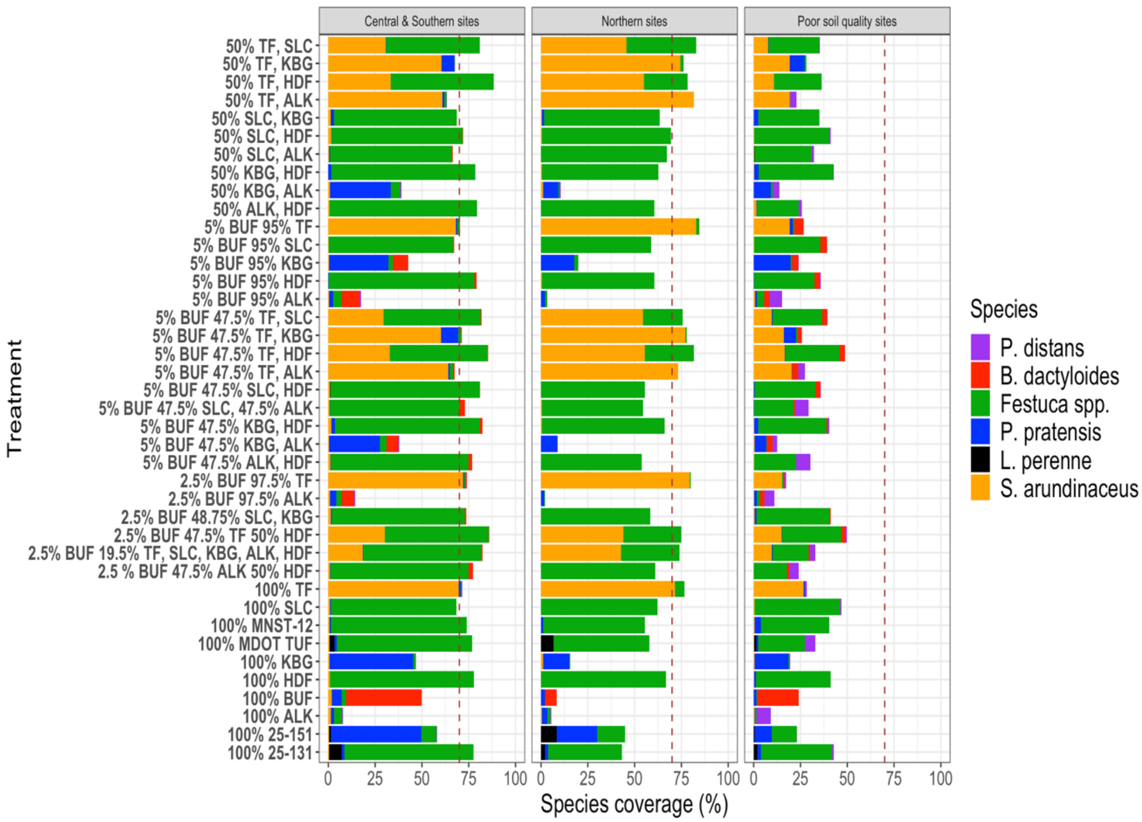

Figure 4.26 Average species composition for the three clusters in the fifth sampling time approximately two years after seeding. Sites seeded in fall 2019 are not included, since data is not available. Northern sites are represented by East Grand Forks. Poor soil quality sites contain Brainerd and Grand Rapids. Central/southern sites include Chatfield, Fergus Falls, Marshall, and Roseville. TF = tall fescue, HDF = hard fescue, SLC = slender creeping red fescue, ALK = alkaligrass, KBG = Kentucky bluegrass, BUF = buffalograss. This figure is intended for a quick comparison between the three clusters since its biological interpretation is reduced due to averaging.

Figure 4.27 Duluth roadside research site before plot one. Numerous coarse fragments allowed the site to be highly thermally conductive containing very high daily and yearly fluctuations in soil temperatures. The planting environment generally reduced vegetation growth and persistence.

Figure 4.28 Chatfield roadside research site. Mowing during droughty conditions experienced in the summer of 2019 and 2020 resulted in some plots, especially ones dominated by fine fescues, to contain a patchwork of turfgrass vegetation.

Figure 4.29 Bemidji roadside research site in the summer of 2020. Winter snowplowing showing resulted in direct damage in some plots from plow and indirect damage from grass being exposed after removal of snow. Greater turfgrass coverage near streetlight (which was not cleared) indicates that maintaining some snow cover over grass of a recent seeding can improve spring coverage.

Figure 4.30 Chatfield roadside research site in the winter of 2019. Plots covered by more than six feet of snow containing salt, sand, and gravel.

Figure 4.31 Fergus Falls roadside research site on May 20, 2020. Plots contain good turfgrass coverage near the end of the third block with regular spacing of quackgrass pressure creeping in from border.

Table 4.1 The nearest weather station to each roadside research site. Data collected from each station began when it was seeded and contained the temperature maximum, minimum, rainfall and snowfall precipitation, and snow depth. The station chosen was the nearest one with the least missing data.

Research site	Station name	Station ID	City	State[a]	Latitude	Longitude
Grand Rapids	Pokegama, MN US	USC00216612	Grand Rapids	MN	47.2508	-93.5861
Grand Rapids[5]	Grand Rapids Frs Lab, MN US	USC00213303	Grand Rapids	MN	47.2436	-93.4975
Brainerd	Brainerd, MN US	USC00210939	Brainerd	MN	46.3433	-94.2086
Brainerd[6]	Brainerd Crow Wing Co Airport, MN US	USW00094938	Brainerd	MN	46.40472	-94.13083
E. G. Forks	Grand Forks University NWS, ND, US	USC00323621	Grand Forks	ND	47.92172	-97.0975
Fergus Falls[1]	Orwell Dam, MN US	USC00216228	Fergus Falls	MN	46.2154	-96.178
Fergus Falls[2]	Breckenridge 3 E, MN US	USC00210974	Breckenridge	MN	46.3047	-96.5216
Roseville	University of MN St. Paul, MN US	USC00218450	St. Paul	MN	44.9902	-93.17995
Marshall	Marshall, MN US	USC00215204	Marshall	MN	44.4716	-95.79019
Chatfield	Rochester International Airport, MN US	USW00014925	Rochester	MN	43.9041	-92.4916
Bemidji[3]	Bemidji, MN US	USR0000MBEM	Bemidji	MN	47.5032	-94.9281
Bemidji[4]	Bemidji, MN US	USC00210643	Bemidji	MN	47.5353	-94.8268
Int. Falls	Int. Falls International Airport, MN US	USW00014918	International Falls	MN	48.5614	-93.3981
Duluth	Duluth International Airport, MN US	USW00014913	Duluth	MN	46.8369	-92.1833
Saint Cloud	St. Cloud Regional Airport, MN US	USW00014926	Saint Cloud	MN	45.5433	-94.0513
Willmar	Willmar 5 N, MN US	USC00219001	Willmar	MN	45.1901	-95.0586
Edina[7]	Mpls St. Paul International Airport, MN US	USW00014922	Minneapolis	MN	44.8831	-93.2289
Worthington	Worthington 2 NNE, MN US	USC00219170	Worthington	MN	43.6449	-95.5802

[1,2]Orwell is much closer but was missing data from Jan. 8-31, 2019, therefore Breckenridge weather data was used to fill that gap. [3]Missing precipitation data. [4]Missing temperature data. [5]Used only to fill in Aug. 2019 and Sep. 2020 missing weather data. [6]Used to fill in Jan. 2021 missing temperature data. Brainerd still missing January snowfall and depth data. [7]Edina weather data appears more skewed from urban heat island effect than other sites.

[a] MN = Minnesota, ND = North Dakota.

Table 4.2 Average soil moisture and other moisture characteristics based on or affected by the soil properties for each site (Saxton et al., 1986).

Research site	Average moisture (%)[ab]	Field capacity (%)[b]	Wilting point (%)[b]	Potential plant available water (%)[b]
Bemidji	6.98 k	22.7 i	13.7 i	8.99 hi
Brainerd	4.31 l	23 i	14.5 ghi	8.58 i
Chatfield	13 g	28.6 ef	18.3 e	10.4 efg
Duluth	7.27 j	25.1 gh	14.1 hi	11 de
E. G. Forks	18.4 e	44 a	27.6 a	16.4 a
Edina	20.8 c	26.9 fg	15.4 fgh	11.6 cd
Fergus Falls	10.2 h	28.4 ef	17.5 e	10.9 def
G. Rapids	9.65 i	24.3 hi	14.1 hi	10.2 efg
Int. Falls	15.4 f	32.6 d	20.7 d	11.9 bc
Marshall	21.3 b	36.1 c	23.5 c	12.7 b
Roseville	20 d	25.2 gh	15.6 fg	9.6 gh
Saint Cloud	13.1 g	26 gh	16 f	9.99 fg
Willmar	21.3 b	30.1 e	17.9 e	12.2 bc
Worthington	24.9 a	40.7 b	25.1 b	15.6 a

[a] Average moisture calculated from all available moisture data points available for each site. This results in a different number of sampling data points per site.
[b] Significant differences are based on Fisher's LSD with no p-value correction applied.

Table 4.3 Average soil chemical and physical characteristics at each research site. Bulk density values are averaged from samples taken at three different distances from the curb within each of the three blocks. Significant differences are based on Fisher's LSD with no p-value correction applied.

Research site	K[c]	OM[a]	Sat. elect. conductivity (mmhos cm^{-1})	Sand (%)	Clay (%)	Soil textural class[b]	Zn[c]	Cu[c]	Fine bulk density (g cm^{-3})	Coarse bulk density (g cm^{-3})
Bemidji	82 e	2.07 fg	1.07 bc	69.6 a	20 f	SCL	2.84 f	0.344 d	1.38 b	1.43 b
Brainerd	78.3 e	3.1 def	0.733 cde	71.2 a	21.7 f	SCL	43.3 a	14.4 a	1.34 b	1.4 b
Chatfield	133 d	2.7 efg	0.767 cde	52.5 cd	31.7 d	SCL	1.43 f	0.379 d	1.22 cde	1.28 cd
Duluth	56 e	2.6 efg	1.63 a	55 bcd	22.1 f	SCL	3.74 def	4.7 b	1.31 bc	1.61 a
E. G. Forks	240 a	4.97 bc	0.633 de	3.93 i	47.5 a	Silty clay	1.71 f	1.4 cd	1.11 efg	1.14 ef
Edina	69.7 e	5.8 ab	1.43 ab	49.2 de	25.4 e	SCL	6.74 c	1.11 cd	1.28 bcd	1.35 bc
Fergus Falls	231 a	5.1 bc	0.967 cd	50.4 d	30 d	SCL	6.17 cd	1.15 cd	1.19 def	1.28 cd
Grand Rapids	59.3 e	1.83 g	0.8 cde	60 b	21.7 f	SCL	2.95 f	1.03 cd	1.58 a	1.71 a
Int. Falls	129 d	6.63 a	1.1 bc	41.2 f	36.7 c	CL	3.49 ef	1.19 cd	0.95 h	1.05 f
Marshall	203 ab	4 cd	0.467 e	34.4 g	42.1 b	Clay	3.41 ef	1.19 cd	1.1 fg	1.18 de
Roseville	74.3 e	5.13 b	0.633 de	61.7 b	25 e	SCL	12.8 b	2.59 c	1.23 cd	1.27 cd
Saint Cloud	142 cd	2.7 efg	1.4 ab	58.3 bc	26.3 e	SCL	2.42 f	0.532 d	1.36 b	1.43 b
Willmar	183 bc	3.43 de	1.53 a	42.5 ef	31.3 d	CL	5.97 cde	1.02 cd	1.29 bcd	1.36 bc
Worthington	170 bcd	5.03 bc	0.833 cde	16.3 h	44.2 b	Clay	2.88 f	1.01 cd	1.05 gh	1.11 ef

[a] OM = organic matter content.

[b] SCL = sandy clay loam, CL = clay loam.

[c] Units of mg kg^{-1}.

Table 4.4 Observed yearly weather summary totals and means from weather stations. Snow depth metrics are not shown.

	2018[c]				2019[c]				2020			
Research site	TMAX[a]	TMIN[a]	PRCP[b]	SNOW[b]	TMAX	TMIN	PRCP	SNOW	TMAX	TMIN	PRCP	SNOW
Bemidji					6.3	-2.6	382	1141	10.8	-1.0	723	1287
Brainerd	4.8	-4.2	214	558	9.5	-2.1	991	2067	11.0	-1.2	780	1316
Chatfield	5.6	-2.8	267	390	10.9	1.2	1403	2342	12.7	2.4	794	1275
Duluth					6.1	-1.6	363	1430	10.3	0.1	541	2127
E. G. Forks	3.0	-5.4	151	599	8.6	-1.4	862	2509	11.2	-0.3	464	1006
Edina					9.4	1.7	307	653	13.6	4.1	759	1432
F. Falls	4.6	-5.7	153	625	9.4	-1.5	759	1457	11.6	-0.5	599	726
G. Rapids	5.2	-3.1	245	204	9.0	-2.4	781	1638	10.6	-1.6	653	979
Int. Falls					5.7	-3.1	356	768	10.3	-2.8	546	1553
Marshall	8.0	-3.8	309	513	11.8	0.1	1164	2197	14.1	1.3	587	1183
Roseville	5.9	-1.7	286	293	10.7	1.4	1091	2212	12.4	2.6	656	1247
St. Cloud					5.3	-3.6	229	592	12.5	1.1	680	1142
Willmar					6.0	-2.8	251	566	12.1	1.0	559	895
Worthin.					8.4	-1.2	349	436	13.1	1.7	578	1255

[a] Average for each site within each year is in units of (° C). TMAX = maximum temperature, TMIN = minimum temperature.
[b] Sum for each site within each year in units of (mm). PRCP = rainfall precipitation, SNOW = snowfall precipitation.
[c] Research sites seeded in 2018 and 2019 showcase the means and sums of what each site received, so not necessarily a full year of weather data, but beginning when the site was seeded.

Table 4.5 Total number of yearly observed cumulative growing degree days at base 0 ° C and 10 ° C for each site beginning by seeding date from the nearest weather location.

	2018		2019		2020[a]		2021[b]	
Research site	0 ° C	10 ° C	0 ° C	10 ° C	0 ° C	10 ° C	0 ° C	10 ° C
Bemidji	0	0	696	177	2902	1120	550	115
Brainerd	411	89	2878	1081	2765	1054	601	127
Chatfield	421	65	3294	1337	3461	1435	783	180
Duluth	0	0	617	156	2871	1084	541	100
E. G. Forks	326	43	2999	1198	3164	1365	553	97
Edina	0	0	908	330	3796	1699	831	205
Fergus Falls	348	63	2969	1151	3143	1313	83	0
G. Rapids	576	155	2773	993	2875	1125	528	111
Int. Falls	0	0	638	136	2650	944	507	102
Marshall	483	79	3434	1488	3651	1654	746	181
Roseville	511	123	3334	1364	3481	1497	324	79
Saint Cloud	0	0	432	101	3315	1371	653	139
Willmar	0	0	555	164	3337	1412	650	153
Worthington	0	0	733	241	3504	1492	202	22

[a] First year to compare total growing degree days between all 14 sites.
[b] Not a complete year of experienced weather data so this column is missing values disproportionately by site.

Table 4.6 Deviation in observed weather data (in 2020) and climate normals (1991-2020) for each research site. The source of the weather data is from the nearest station. More negative values represent cooler temperatures, less rainfall, or less snowfall precipitation than normal (1991-2020). TMAX = maximum temperature, TMIN = minimum temperature, PRCP = rainfall precipitation, SNOW = snowfall precipitation.

	Deviation between observed and expected climate normal			
Research site	TMAX (° C)[a]	TMIN (° C)[a]	PRCP (mm)[b]	SNOW (mm)[b]
Bemidji	0.52	-0.11	33.4	92.9
Brainerd	0.30	0.50	8.0	92.4
Chatfield	0.50	0.28	-86.8	-66.9
Duluth	0.78	0.53	-251.0	-165.0
E. G. Forks	0.70	0.20	-112.0	-259.0
Edina	0.58	0.77	-43.7	129.0
Fergus Falls	1.12	0.68	0.04	233.0
G. Rapids	0.77	-0.12	-46.4	-108.0
Int. Falls	0.81	0.15	-98.4	-303.0
Marshall	0.79	-0.73	-148.0	33.5
Roseville	-0.46	-0.27	-179.0	515.0
Saint Cloud	0.45	0.63	-43.5	-89.5
Willmar	0.58	0.42	-216.0	-309.0
Worthington	0.59	0.31	-205.0	64.4

Table 4.7 Correlation matrix of remaining climate and soil variables used in the cluster analysis and ordination plotting. The more negative the value, the darker red the corresponding cell will be, while the more positive the value, the darker green its corresponding cell will be. LAT = latitude, SNWD = snow depth, SNOW = snowfall precipitation, SEC = saturated paste extract electrical conductivity, OM = organic matter content, BD = bulk density, PRCP = rainfall precipitation, TMAX = temperature maximum, TMIN = temperature minimum.

	TMAX	TMIN	PRCP	SNOW	SNWD	SAND	CLAY	OM	SEC	Total BD	Fine BD	LAT
TMAX	1.000											
TMIN	0.833	1.000										
PRCP	0.228	0.305	1.000									
SNOW	-0.230	0.022	0.026	1.000								
SNWD	-0.774	-0.636	-0.024	0.473	1.000							
SAND	-0.234	-0.080	0.710	0.158	0.317	1.000						
CLAY	0.311	0.030	-0.617	-0.214	-0.390	-0.939	1.000					
OM	0.332	0.280	-0.321	-0.084	-0.483	-0.547	0.552	1.000				
SEC	-0.168	0.122	-0.021	0.359	0.191	0.232	-0.414	-0.162	1.000			
Total BD	-0.356	-0.115	0.308	0.156	0.398	0.663	-0.818	-0.751	0.417	1.000		
Fine BD	-0.245	-0.047	0.467	-0.085	0.309	0.688	-0.817	-0.738	0.281	0.940	1.000	
LAT	-0.866	-0.820	-0.340	0.123	0.724	0.052	-0.118	-0.100	0.074	0.166	0.097	1.000

Table 4.8 The average turfgrass species monoculture coverage and standard deviation (shown in parenthesis) at different clusters and across all research sites. Data is from the third sampling time which was collected approximately one year after seeding at each research site. Means comparison show statistical differences among monoculture species within each locality/cluster category. Means comparison are based on Fisher's LSD test with no p-value correction applied.

	Locality/cluster			
Monoculture species	Northern	Central/southern	Poor soil quality	All research sites
Alkaligrass	26.1 c (15.5)	11.8 e (19.9)	29.4 abc (25)	18.9 d (22.1)
Buffalograss	8.61 c (11.8)	23.9 d (17.2)	41.1 a (18.5)	26.6 d (19.7)
Hard fescue	81.1 a (10.1)	85.5 a (9.7)	38.5 a (23.3)	71.4 a (25.6)
Kentucky bluegrass	54.2 b (13.4)	53.1 c (20)	19.4 bc (15.5)	43.7 c (23.5)
Slender c. red fescue	89.7 a (9)	83.3 ab (17)	36.4 ab (26.7)	70.8 a (29.2)
Tall fescue	59.4 b (26.4)	73.5 b (21.9)	16.7 c (21.8)	55.3 b (33.4)
Average[a]	53.2 a (32.3)	55.2 a (33.7)	30.3 b (23.3)	47.8 (32.7)

[a] Statistical means comparing average among clusters.

CHAPTER 5: ECONOMICS RESEARCH DATA ANALYSIS AND COST PREDICATION TOOL DEVELOPMENT

5.1 INTRODUCTION

Publicly available cost assessments for establishing roadside turfgrasses in Minnesota do not exist. To address this need, our goal was to develop a detailed enterprise budget to record the costs (i.e. labor, water, seed, sod, fertilizer, etc.) for establishing roadside sites. We intend for this tool to be used by local and state officials in determining costs associated with roadside installations and which types or combinations of turfgrasses are most cost effective, while also generating optimal performance.

5.2 METHODS

5.2.1 Data collection

Cost assessment data were obtained by interviewing industry experts and roadside turfgrass managers. First, we received input from seeding contractors in order to better understand the process of installing a new roadside turf area. We then collected construction input quantity and cost data from MnDOT (http://transport.dot.state.mn.us/PostLetting/ItemsUsedForPastProjects.aspx). The data include construction projects in Minnesota that involve low maintenance turf and high maintenance turf establishments. Table 5.1 shows a data sample which includes input quantity and cost.

In addition, Dwayne Stenlund provided plan sheets data of previous projects (http://www.dot.state.mn.us/metro/finaldesign/sampleplan.html). Based on the plan sheets, we specifically looked into turf establishment plans, erosion control plans, soil and construction notes and general layout for each project. The plan sheets specify the construction site and decompose input quantity into more granular levels. We summarized the plan sheets and investigated the conditions where there are similar quantity patterns between inputs. For example, we found that hydraulic erosion control products are quantitatively correlated with disk anchoring, mulch, seed mixes, but such correlations depend on the type of rapid stabilization methods. Another example is we found mulch is associated with the use of disk anchoring which depends on hydraulic erosion control products. We have applied these identified patterns for the development of the cost prediction models.

5.2.2 Model development

After cleaning and analyzing the data, we developed cost prediction models that can be used to estimate the costs for future roadside turfgrass establishment projects. In the first year, we developed a model that separates the stages of turfgrass establishment. The model required more than 30 inputs. Based on the feedback from the project committee, in the new tool, we reduced the number of inputs which still maintains a good level of accuracy. To achieve this, we divided the dataset into three subgroups, and developed economic cost prediction models for each subgroup. The new prediction tool requires fewer inputs, 16 inputs at most. The average prediction accuracy of these models is 95.4%. Eighty-five percent of the data have a prediction accuracy at the level of 90% to 100%.

The reason why we developed separate models for projects with different cost levels is the cost of turf establishments is determined by key variables, such as sodding size, hydraulic matrix, etc., and such input quantities may not affect the total cost of larger-scale projects in the same way as smaller-scale projects. For example, the cost for certain input might decrease when the scale of project increases. It is not practical to use the same model to predict the cost of 0.5-acre project and the cost of 50-acre project. Thus, to achieve accurate prediction results, we developed three prediction models depending on the usage levels of hydraulic matrix and topsoil, seeding acreage, sodding acreage, etc. The three models require similar number of inputs. After the models were developed, we programmed the models into Excel and generated a user-friendly cost prediction tool (see attached Excel file). Based on input from potential users, the research team debugged the tool.

5.3 RESULTS

Table 5.2 shows an example of the prediction models. The first column are the inputs and the second column are the coefficients associated with inputs and some of them are the coefficients for the interactions between inputs.

The interface of the first step of prediction tool looks like the one in Figure 5.1, where there are two buttons a user can click on. The first button requires the user to enter input quantities step by step using pop-up question boxes. One example of the pop-up question boxes is shown in Figure 5.2. Some questions require the user to enter input quantities and some require the user to answer Yes/No type of questions. The information the user provides will be automatically summarized as a table, which is shown in Figure 5.3.

After the input quantities are entered, the second button “Assign Worksheet” leads the user to certain worksheet to determine the total cost. A pop-up box leading to the appropriate spreadsheet is shown in Figure 5.4 which indicates how users are led to a worksheet. Then the user can go to the assigned worksheet, the information she/he provided will automatically updated in this worksheet, and the first button asks to enter a few more input quantities using pop-up question boxes, and the total costs will be estimated automatically (Figure 5.5).

The prediction tool can predict the total cost for roadside projects. It can also be used to analyze the cost change when certain input quantity changes. However, many inputs are substitutes or complements, changing one input quantity often means the changes in other inputs’ quantities. For example, to see how the decreasing in seeding area impacts the total cost, the sodding area, mulch material, and soil bed preparation need to be changed. This is because turf establishment requires that in order to deliver sod to the work site, soil bed preparation is needed to avoid delays in placing the sod, and straw or hydro mulch is incorporated into soil to stabilize exposed areas. Users need to consider all these other possible adjustments when one input quantity is changed. When any combination of inputs is considered unreasonable, the prediction tool will show “Please double check if the amounts of inputs are reasonable.”

5.4 CONCLUSION

Using the newly developed tool, we can compare the costs for using sod and seed, along with the different types of grass species and seed mixtures that are available to determine which types or combinations of grass types are the most cost-efficient or generate the optimal performance while requiring the lowest cost. By combining the cost data with the grass performance data from the field research of this project, we can evaluate the economic feasibility of adopting different turfgrass species on various roadside sites and the potential tradeoffs between cost and performance. Future iterations can integrate turfgrass mixture performance to show the benefits or risks associated with higher-cost grass seed options.

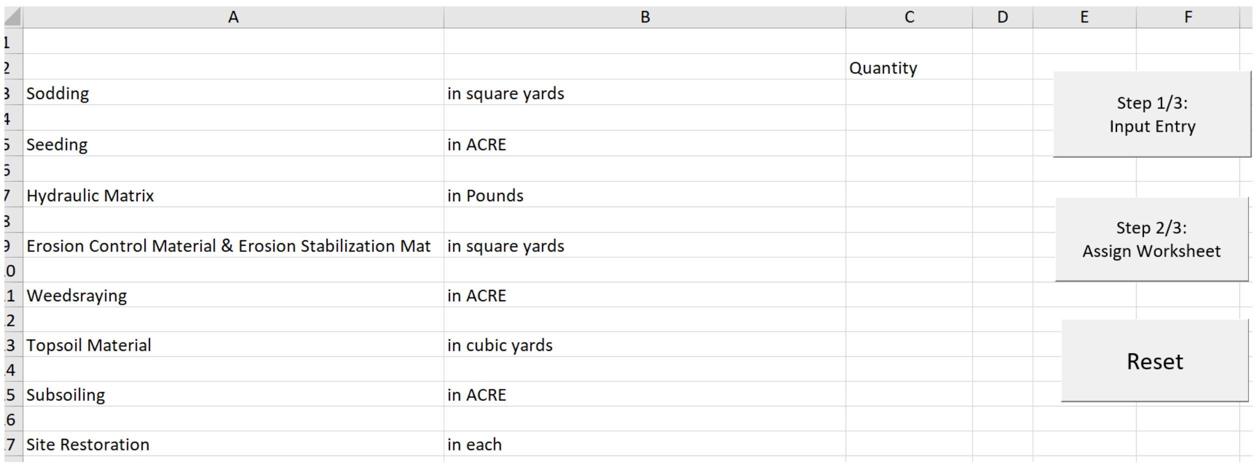

Figure 5.1 The first interface of the prediction tool.

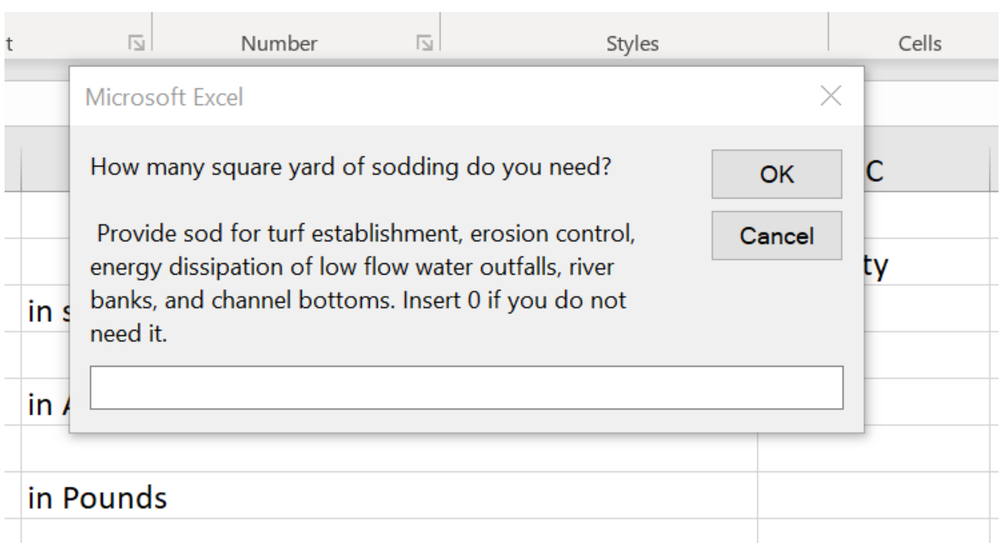

Figure 5.2 Pop-up box asking for inputs in the prediction tool.

		Quantity
Sodding	in square yards	0
Seeding	in ACRE	1.5
Hydraulic Matrix	in Pounds	0
Erosion Control Material & Erosion Stabilization Mat	in square yards	7200
Weedsraying	in ACRE	1
Topsoil Material	in cubic yards	0
Subsoiling	in ACRE	0
Site Restoration	in each	0

Step 1/3: Input Entry

Step 2/3: Assign Worksheet

Reset

Figure 5.3 The summary table after inputs are entered.

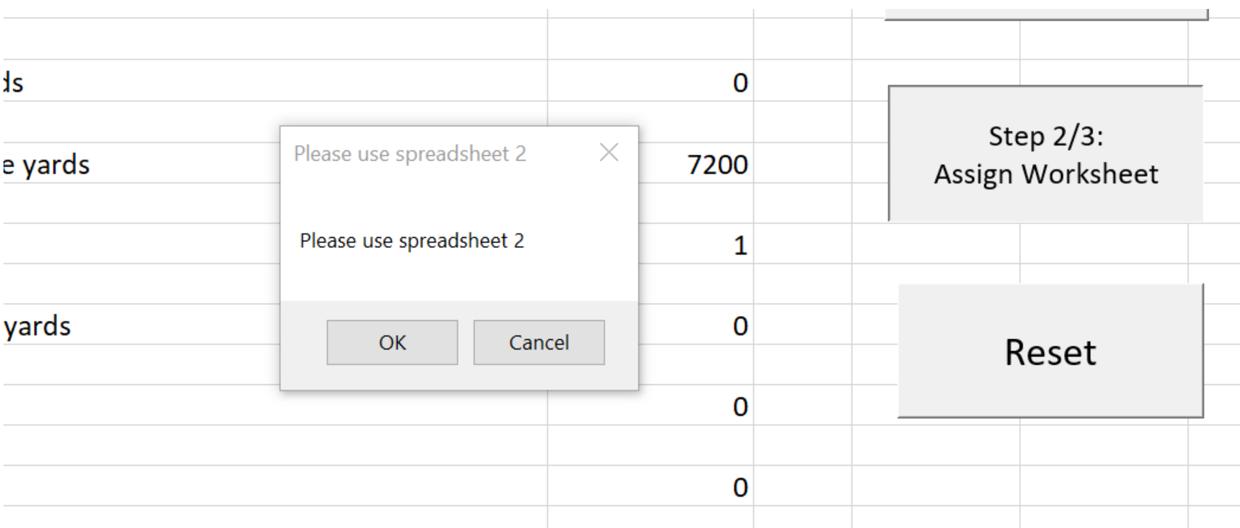

Figure 5.4 Pop-up box leading to the assigned spreadsheet.

		Quantity		
Sodding	in square yards	0		
Seeding	in ACRE	1.5	Step 3/3: Input Entry and Cost Prediction	
Hydraulic Matrix	in Pounds	0	Total Cost	15911.32
Erosion Control Material & Erosion Stabilization Mat	in square yards	7200		
Weedsraying	in ACRE	1		
Topsoil Material	in cubic yards	0		
Subsoiling	in ACRE	0		
Site Restoration	in each	0		

Figure 5.5 The assigned spreadsheet and total cost prediction.

Table 5.1 Input quantity and cost data sample.

Contract ID	130234	140001	140015	140023	140052
Boulevard topsoil borrow	0	0	0	0	0
Common topsoil borrow	0	0	0	2753	0
Compost grade 2	9565	0	479	298	3867
Fertilizer type 1	0	0	0	0	0
Fertilizer type 2	0	0	0	0	0
Fertilizer type 3	0	875	3073	1221	0
Fertilizer type 4	0	97	38	0	0
Soil tracking	0	0	0	0	0
Sub-soiling	0	0	0	0	0
Total cost	45093.04	32404.60	91605.75	50271.13	310192.79

Table 5.2 An example of the prediction models.

Model	Coefficient
Seeding	1712.36
Sodding	-42.36
Mulch (If rapid stabilization method 4 is not chosen)	231.33
Mulch (If rapid stabilization method 4 is chosen)	4397.85
Topsoil	1.19
Total Hydraulic (If subsoiling is not chosen)	-0.82
Total Hydraulic (If subsoiling is chosen)	1.26
Total Erosion (If subsoiling is not chosen)	5.83
Total Erosion (If subsoiling is chosen)	-0.60
Total Mowing + Total Weed Spraying (If subsoiling is not chosen)	-6829.89
Total Mowing + Total Weed Spraying (If subsoiling is chosen)	2329.65
Lime	705.25
Subsoiling	5649.17
Disk Anchoring (If rapid stabilization method 1 is not chosen)	-6044.83
Constant	28201.49

CHAPTER 6: CONCLUSION AND FINAL RECOMMENDATIONS

6.1 NEW SEED MIXTURES

From our findings we qualitatively develop the following roadside turfgrass seed mixtures for Minnesota (Table 6.1). These mixtures are recommended in addition to the currently recommended mixtures. We limit the species recommendations to ones that have been directly tested and evaluated in this experiment. All mixtures are designed based on pure live seed ratio and then the relative weight is calculated from that ratio for each constituent species. In discussing all seed mixtures below, we refer to seed ratio, unless noted by weight.

We recognize there are some limitations in the regionality of our clusters in Minnesota; consider Duluth, which is closer to Lake Superior and in a different plant hardiness zone than areas located farther inland (USDA Plant Hardiness Zone Map, 2012). Additionally, we recognize that southeastern and southwestern Minnesota can be distinguished by a precipitation gradient, but both are grouped within the central/southern cluster. These areas of the state could be later delineated. It is important to remember that clustering is a simplification process explaining a portion, and not of all the variability along roadsides tested in this experiment. The plant hardiness zones are also changing with temperature trends in Minnesota. Future testing and validation of these clusters will be needed over time, since species' zones of adaptation will change (McKenney et al., 2007).

We want to stress the importance of including multiple species in a seed mixture. If the area and time are expanded for the use of these mixtures, then what appears to be an overly complicated mixture for a single site, may be a more appropriate one. Larger areas have greater nuances in sunlight quality and quantity, soil chemical and physical characteristics, weather and climate, maintenance, and other disturbance factors. We intend for these mixture recommendations to be effective over larger areas and longer periods of time.

6.1.1 Northern cluster mixture

The northern mixture was designed similarly to a Michigan DOT mixture (MDOT TUF), which previously performed well in several states and at harsh sites (Watkins et al., 2019). Our northern mixture differed from MDOT TUF to include no perennial ryegrass and slightly more weeping alkaligrass (from 16.30% to 20%), and we added tall fescue (5%) due to some adaptation of this species at the East Grand Forks research site in northwest Minnesota. Tall fescue was included at a low rate because it germinates quickly and has the potential to overwhelm a mixture in the seedling stage. We also approximately flipped the ratio of *F. ovina*: *F. rubra* in this mixture compared to the Michigan mixture, since hard fescue showed similar performance to slender creeping red fescue at sites located in this region. (Turfgrass plots at International Falls are shown in Figure 6.1.)

6.1.2 Central/southern cluster mixture

The central/southern regional turfgrass mixtures included more tall fescue (+5%) and less weeping alkaligrass (-10%) than the northern mixture. The central/southern mixture differed from MNST-12 turfgrass seed mixture (Minnesota Crop Improvement Association, 2021) by including tall fescue (from 0 to 10%) and weeping alkaligrass (from 0 to 10%) and a higher proportion of *F. ovina* compared to the *F. rubra* complex (2:1 *F. ovina* to *F. rubra* for the central/southern cluster mixture compared to 0.25-1:1 by weight in the MNST-12 mixture). Tall fescue was included at a slightly greater ratio in the central/southern cluster due to it being more adapted to the warmer temperatures in this area of Minnesota. Alkaligrass showed poorer performance to warmer, drier conditions in this area of the state, so its ratio was lowered, although some of these conditions existed at the Duluth site and alkaligrass was persisting. The ratio of fine fescue species was modified since 'Gladiator' hard fescue has shown less stress in the middle of the growing season in this region and contains a lower standard deviation than SeaMist slender creeping red fescue. The persistence of hard fescue in Minnesota along roadsides has been identified previously by Friell et al. (2015). (Photos showing turfgrass plots classified in this cluster are shown in Figures 6.2-4.)

6.1.3 Poor soil quality cluster mixture

The poor soil quality cluster contained more alkaligrass than the northern cluster (+10%) so a significant portion of weeping alkaligrass was included in the mixture. In an experiment simulating roadsides that were heavily salted and contained poor soils, it was shown to be the only species to survive in an experiment (Watkins et al., 2019). In our study, alkaligrass did well at three of the four research sites clustered within the poor soil quality cluster but still tended to decrease over time. Tall fescue was not included in the mixture, since it was nearly absent at three of the four research sites, and had previously shown susceptibility to winter stresses along roadsides in Minnesota (Friell et al., 2015). The conditions at these sites seemed to be exacerbating the death of tall fescue. Kentucky bluegrass was included at a low rate in this mixture (5%), since its performance is limited, but adapted cultivars could provide some benefit in certain roadside situations of this type. Hard and slender creeping red fescue were included at a similar rate because slender creeping red fescue has shown greater salt tolerance in these conditions. Buffalograss was included at 5%, since it has natural adaptations to moisture and temperature extremes and its performance at the Duluth site showed that it can survive difficult winter conditions. Buffalograss' performance in excessively sandy soils can be limited based on our results from Brainerd, although Severmutlu et al. (2011) found it may not be a significant factor for turf-type cultivars in a warm climate. Additional research to identify and select for buffalograss cultivars better adapted to roadsides would be beneficial.

To identify a poor soil quality site, we recommend more soil testing before seeding. We define a poor soil quality site as meeting two of the three following criteria: soil sand content > 55%, organic matter <= 2.2% (Hopkinson et al., 2016), and bulk density >=1.6 g cm^{-3}, or if the site meets one of the three following criteria: soil sand content > 70%, organic matter <= 1.7% (Hopkinson et al., 2016), or bulk density >= 1.8 g cm^{-3}. There are also more species potentially adapted to this cluster that were not tested in our experiment, so this mixture would benefit from additional research. (Turfgrass plots classified in this cluster are shown in Figure 6.5-6.)

6.2 OTHER CONSIDERATIONS AND SPECIES WITH POTENTIAL FOR ROADSIDES

Perennial ryegrass was not recommended to remove risk of compromising a mixture. For example, even if the seed ratio was designed properly, if the total seeding rate was doubled, then perennial ryegrass seeding density was effectively doubled for that given area, which has the potential to limit other species in a mixture (Dunn et al., 2002; Engel & Trout, 1980; Henensal et al., 1980).

Previous MnDOT recommendations have included a blend of Kentucky bluegrass within a mixture for roadsides (MnDOT, 2014), and we would continue to encourage this practice since it does offer benefits in seed mixture diversity. However, preference should be given to compatible species diversity before additional cultivar diversity. We also know that older varieties of Kentucky bluegrass generally have been performing better on roadsides (Friell & Watkins, 2020), so newer is not always better.

Additional species could be further investigated in roadside turfgrass mixtures. These species could be more applicable for the poor soil quality cluster and have shown some potential in historical research. Western wheatgrass has shown compatibility with low-maintenance turfgrass species (Bunderson, 2007; Robins & Bushman, 2020) and its natural drought tolerance could yield it to be a good component for sandy roadsides. Canada bluegrass, Russian wildrye, and sand dropseed have been observed to perform well on excessively sandy roadside sites in Minnesota (Foote et al., 1978; Henslin, 1982). Poverty dropseed was found in the soil seed bank at 10 of 14 roadside research sites and has been observed growing along many roadsides in Minnesota. Purple lovegrass was observed growing at the sandy Bemidji research site. White clover was included in historical MnDOT mixtures and is well adapted to many soil textures (Lane et al., 2019). Common yarrow (*Achillea millefolium*) has been observed growing at the Duluth research site and tolerating drought conditions at other roadside research sites.

6.3 LIMITATIONS

Our study contained limitations that skewed the relative performance of some species particularly in the coverage data. Our sampling timing in the spring occurred when tall fescue was not always actively growing (but still green) and occasionally when buffalograss had not even greened up (Figure 6.7). Therefore, the spring sampling dates contained some bias of less coverage of these species. This occurred at some fall sampling times as well, such as at Worthington or Marshall when sampling occurred in November, because at this time, the coverage of buffalograss was beginning to go dormant and leaf tissue was not as expansive compared to mid-summer. We recommend one mid-summer (June-August) sampling in Minnesota for all future roadside turfgrass experiments, especially when they contain a warm-season species. A summer sampling would also show reductions of slender creeping red fescue at southern Minnesota sites.

Additionally, the time period over which we sampled the roadside vegetation was still relatively short compared to some previous regional roadside work in Minnesota. We especially noticed buffalograss and Kentucky bluegrass coverage to be increasing at some sites over time. A length of five years seems more sufficient as a minimum amount of time to evaluate coverage changes, especially in a mixture setting.

6.4 FUTURE RESEARCH IDEAS

- Based on the significance of the dendrogram cluster, it would be most beneficial to continue to test and improve the mixture for the poor soil quality cluster along roadsides in Minnesota.
- The ratios and seeding timing of warm- and cool-season grass mixtures should be investigated. Specifically, a seedling competition study between buffalograss, hard fescue, and Kentucky bluegrass would be beneficial. Treatments could consist of planting date, mowing height, and different mixture ratios and coverage could be evaluated over time similar to Brede and Duich (1984b). This could improve the recommendation of the poor soil quality cluster mixture (Table 6.1).
- We recommend identifying, improving, and testing germplasm for roadsides. A couple characteristics that could be selected for would be improved winter hardiness of tall fescue and overwintering of buffalograss on roadsides in Minnesota.
- An optimum planting date and range for turfgrass mixtures could be calculated based on the ideal or adequate number of growing degree days before winter in both geographical clusters.
- In the future, it will be important to identify whether Minnesota continues to trend mostly warmer and wetter (NOAA; MnDNR, State Climatology Office) or becomes dryer and warmer, as well as the relative deviation in these trends. Based on the current changes and trajectory in climate, turfgrass mixtures for roadsides in Minnesota should be open to future modification.
- We encourage testing and refinement of these seeding clusters for roadside turfgrass mixtures in Minnesota. Cluster and species refinement could consist of modification, addition, or subtraction of regions. Species modification could consist of adding or removing species, modifying species ratios, or the addition or subtraction of cultivar diversity. All modifications should be tested and recommended by pure live seed ratio.

6.5 CONCLUSION AND FINAL RECOMMENDATIONS FOR MNDOT

To improve the persistence of turfgrasses vegetation along roadsides in Minnesota, we recommend three new turfgrass seed mixtures for the state delineated by cluster. These mixtures are recommended in addition to current mixtures. Two clusters are geographical, and one is based on soil quality (Table 6.1). The northern geographical cluster includes cities from east to west, Hinckley, Brainerd, and Fargo, and northward. The central/southern geographical cluster is south of those cities. A poor soil quality site is defined as meeting two of the three following criteria: soil sand content > 55%, organic matter <= 2.2% (Hopkinson et al., 2016), and bulk density >=1.6 g cm^{-3}, or if the site meets one of the three following criteria: soil sand content > 70%, organic matter <= 1.7% (Hopkinson et al., 2016), or bulk density >= 1.8 g cm^{-3}. Mixture recommendations are limited to the tested species in this experiment, and additional species may provide value, especially for sites containing poor soil quality. All seed mixtures are designed based on pure live seed ratio and then the relative weight is calculated for each constituent species.

Figure 6.1 Turfgrass plots at the International Falls research site. This photo was taken on May 26, 2021, approximately a year and a half after seeding.

Figure 6.2 Turfgrass plots at the Edina research site. This photo was taken in Oct. 2021, approximately a year after seeding. Fence was installed to prevent municipality maintenance.

Figure 6.3 Turfgrass plots at the Worthington research site. This photo was taken on Apr. 16, 2021, approximately a year and a half after seeding. Plots are showing some salt damage from recent winter. The plot in the foreground is number 120.

Figure 6.4 Turfgrass plots at the St. Cloud research site. This photo was taken on May 19, 2020, the first spring after seeding. Plots are showing winter damage. Differences in species abundance are shown within a plot. Plots with excessive turfgrass death near the road contained tall fescue and plots with excessive turfgrass death further from the road (see plots closer to hydrant) contained alkaligrass.

Figure 6.5 Turfgrass plots at the Grand Rapids research site classified as a poor soil quality site. This photo was taken on July 30, 2020. Plots are showing relatively sparse grass coverage with considerable volunteer legume abundance.

Figure 6.6 Two turfgrass plots at the Duluth research site classified as a poor soil quality site. This photo was taken on May 25, 2021. Plots are showing relatively sparse grass coverage with some volunteer legume abundance. The plot in the foreground is dominated by alkaligrass and the one further from view is dominated by buffalograss greening up from winter dormancy.

Figure 6.7 Two turfgrass plots at the Marshall research site. This photo was taken on Nov. 6, 2020, approximately two years after seeding. The plot on the left is dormant buffalograss and the one on the right contains mostly tall fescue. Dormancy of buffalograss and occasionally tall fescue especially in the spring reduced relative observed coverage.

Table 6.1 Recommended turfgrass seed mixtures for different seeding clusters in the state of Minnesota. PLS = pure live seed, PLW = pure live weight.

Seeding cluster [a]	Species type	Scientific name	Common name	PLS (%)	PLW (%) [b]
North	Cool season	*Puccinellia distans*	Weeping alkaligrass	0.20	0.07
North	Cool season	*Poa pratensis*	Kentucky bluegrass [c]	0.20	0.10
North	Cool season	*Schedonorus arundinaceus*	Tall fescue	0.05	0.13
North	Cool season	*Festuca brevipila*	Hard fescue	0.35	0.41
North	Cool season	*Festuca rubra* ssp. *littoralis*	Slender creeping red fescue	0.20	0.30
Central/southern	Cool season	*Puccinellia distans*	Weeping alkaligrass	0.10	0.03
Central/southern	Cool season	*Poa pratensis*	Kentucky bluegrass [c]	0.20	0.08
Central/southern	Cool season	*Schedonorus arundinaceus*	Tall fescue	0.10	0.23
Central/southern	Cool season	*Festuca brevipila*	Hard fescue	0.40	0.40
Central/southern	Cool season	*Festuca rubra* ssp. *littoralis*	Slender creeping red fescue	0.20	0.26
Poor soil quality	Cool season	*Puccinellia distans*	Weeping alkaligrass	0.30	0.06
Poor soil quality	Cool season	*Poa pratensis*	Kentucky bluegrass [c]	0.05	0.01
Poor soil quality	Warm season	*Buchloe dactyloides*	Buffalograss	0.05	0.47
Poor soil quality	Cool season	*Festuca brevipila*	Hard fescue	0.30	0.20
Poor soil quality	Cool season	*Festuca rubra* ssp. *littoralis*	Slender creeping red fescue	0.30	0.26

[a] Additional research is recommended to improve the development of the seed mixture for the poor soil quality cluster, since this mixture is based only on what species we tested, and from evaluating historical Minnesota roadside turfgrass literature and personal field observations, other species are likely applicable and beneficial.

[b] Weight ratios were calculated by collecting standard seed weight from my calculations and other sources (Beard, 1973; Engelhardt, 2016; Hollman et al., 2018; USDA plant fact sheet).

[c] Kentucky bluegrass seed weight can vary by a factor of almost three times depending on the cultivar and seed lot (Christians et al., 1979).

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APPENDIX A
TABLE OF OBSERVED SEED BANK VEGETATION

Seeding year refers to the year that the field trial was established, and seed bank soil collected from the field.

Research site	Seeding year	Scientific name	Common name
Bemidji	2019	*Chenopodium pratericola*	Desert goosefoot
Bemidji	2019	*Matricaria discoidea*	Pineapple weed
Bemidji	2019	*Conyza canadensis*	Horseweed
Bemidji	2019	*Euphorbia geyeri*	Dune spurge
Bemidji	2019	*Medicago lupulina*	Black medic
Bemidji	2019	*Juncus tenuis*	Path rush
Bemidji	2019	*Oxalis spp.*	Wood-sorrel
Bemidji	2019	*Eragrostis spectabilis*	Purple lovegrass
Bemidji	2019	*Sporobolus cryptandrus*	Sand dropseed
Bemidji	2019	*Sporobolus vaginiflorus*	Poverty dropseed
Bemidji	2019	*Digitaria ischaemum*	Smooth crabgrass
Bemidji	2019	*Panicum capillare*	Witchgrass
Bemidji	2019	*Setaria viridis*	Green foxtail
Bemidji	2019	*Festuca arundinacea*	Tall fescue
Bemidji	2019	*Poa pratensis*	Kentucky bluegrass
Bemidji	2019	*Fallopia convolvulus*	Black bindweed
Bemidji	2019	*Potentilla argentea*	Silvery cinquefoil
Bemidji	2019	*Verbascum thapsus*	Great mullein
Bemidji	2019	*Typha augustifolia*	Narrow-leaf cattail
Bemidji	2019	*Verbena bracteata*	Carpet vervain
Brainerd	2018	*Chenopodium album*	Common lambsquarter
Brainerd	2018	*Ambrosia artemisiifolia*	Common ragweed
Brainerd	2018	*Matricaria discoidea*	Pineapple weed
Brainerd	2018	*Tanacetum vulgare*	Common tansy
Brainerd	2018	*Conyza canadensis*	Horseweed
Brainerd	2018	*Solidago altissima*	Tall goldenrod
Brainerd	2018	*Carpinus caroliniana*	Ironwood
Brainerd	2018	*Coronopus didymus*	Lesser swinecress
Brainerd	2018	*Stellaria media*	Common chickweed
Brainerd	2018	*Trifolium arvense*	Rabbit-foot clover
Brainerd	2018	*Juncus spp.*	Unknown rush2
Brainerd	2018	*Juncus tenuis*	Path rush
Brainerd	2018	*Veronica peregrina*	Purslane speedwell
Brainerd	2018	*Sporobolus vaginiflorus*	Poverty dropseed
Brainerd	2018	*Phalaris arundinacea*	Reed canarygrass
Brainerd	2018	*Poa pratensis*	Kentucky bluegrass
Brainerd	2018	*Populus deltoides*	Plains cottonwood
Brainerd	2018	*Typha spp.*	Cattail
Chatfield	2018	*Amaranthus spp.*	Pigweed
Chatfield	2018	*Chenopodium album*	Common lambsquarter
Chatfield	2018	*Solidago rigida*	Ridgid goldenrod
Chatfield	2018	*Symphyotrichum pilosum*	Awl aster
Chatfield	2018	*Coronopus didymus*	Lesser swinecress
Chatfield	2018	*Silene noctiflora*	Nightflowering catchfly
Chatfield	2018	*Euphorbia spp.*	Spurge
Chatfield	2018	*Trifolium repens*	White clover

Research site	Seeding year	Scientific name	Common name
Chatfield	2018	*Oxalis spp.*	Wood-sorrel
Chatfield	2018	*Plantago major*	Broadleaf plantain
Chatfield	2018	*Sporobolus vaginiflorus*	Poverty dropseed
Chatfield	2018	*Digitaria ischaemum*	Smooth crabgrass
Chatfield	2018	*Digitaria sanguinalis*	Large crabgrass
Chatfield	2018	*Setaria glauca*	Yellow foxtail
Chatfield	2018	*Poa pratensis*	Kentucky bluegrass
Chatfield	2018	*Urtica dioica*	Stinging nettle
Chatfield	2018	*Verbena hastata*	Blue vervain
Duluth	2019	*Chenopodium album*	Common lambsquarter
Duluth	2019	*Chenopodium standleyanum*	Woodland goosefoot
Duluth	2019	*Ambrosia artemisiifolia*	Common ragweed
Duluth	2019	*Tanacetum vulgare*	Common tansy
Duluth	2019	*Gypsophila muralis*	Low baby's-breath
Duluth	2019	*Plantago major*	Broadleaf plantain
Duluth	2019	*Sporobolus vaginiflorus*	Poverty dropseed
Duluth	2019	*Agrostis stolonifera*	Creeping bentgrass
Duluth	2019	*Festuca rubra*	Red fescue
Duluth	2019	*Lolium perenne*	Perennial ryegrass
Duluth	2019	*Poa pratensis*	Kentucky bluegrass
Duluth	2019	*Polygonum aviculare*	Prostrate knotweed
Duluth	2019	*Androsace occidentalis*	Western rock-jasmine
Duluth	2019	*Typha augustifolia*	Narrow-leaf cattail
East Grand Forks	2018	*Matricaria discoidea*	Pineapple weed
East Grand Forks	2018	*Conyza canadensis*	Horseweed
East Grand Forks	2018	*Euphorbia spp.*	Spurge
East Grand Forks	2018	*Lotus corniculatus*	Birdsfoot trefoil
East Grand Forks	2018	*Medicago lupulina*	Black medic
East Grand Forks	2018	*Plantago major*	Broadleaf plantain
East Grand Forks	2018	*Eragrostis cilianensis*	Stinkgrass
East Grand Forks	2018	*Sporobolus vaginiflorus*	Poverty dropseed
East Grand Forks	2018	*Setaria viridis*	Green foxtail
East Grand Forks	2018	*Poa pratensis*	Kentucky bluegrass
East Grand Forks	2018	*Typha spp.*	Cattail
East Grand Forks	2018	*Verbena bracteata*	Carpet vervain
Edina	2019	*Cerastium fontanum*	Mouse-ear chickweed
Edina	2019	*Euphorbia maculata*	Spotted spurge
Edina	2019	*Juncus dudleyi*	Dudley's rush
Edina	2019	*Plantago major*	Broadleaf plantain
Edina	2019	*Veronica peregrina*	Purslane speedwell
Edina	2019	*Digitaria sanguinalis*	Large crabgrass
Edina	2019	*Polygonum aviculare*	Prostrate knotweed
Edina	2019	*Portulaca oleracea*	Common purslane
Edina	2019	*Urtica dioica*	Stinging nettle
Edina	2019	*Verbena bracteata*	Carpet vervain
Fergus Falls	2018	*Chenopodium album*	Common lambsquarter
Fergus Falls	2018	*Symphyotrichum pilosum*	Awl aster
Fergus Falls	2018	*Artemisia spp.*	Wormwood
Fergus Falls	2018	*Lactuca serriola*	Prickly lettuce
Fergus Falls	2018	*Euphorbia spp.*	Spurge
Fergus Falls	2018	*Lotus corniculatus*	Birdsfoot trefoil
Fergus Falls	2018	*Medicago lupulina*	Black medic

Research site	Seeding year	Scientific name	Common name
Fergus Falls	2018	*Trifolium repens*	White clover
Fergus Falls	2018	*Oxalis spp.*	Wood-sorrel
Fergus Falls	2018	*Sporobolus vaginiflorus*	Poverty dropseed
Fergus Falls	2018	*Digitaria ischaemum*	Smooth crabgrass
Fergus Falls	2018	*Digitaria sanguinalis*	Large crabgrass
Fergus Falls	2018	*Portulaca oleracea*	Common purslane
Grand Rapids	2018	*Matricaria discoidea*	Pineapple weed
Grand Rapids	2018	*Spergularia rubra*	Red sand-spurrey
Grand Rapids	2018	*Juncus interior*	Inland rush
Grand Rapids	2018	*Mollugo verticillata*	Carpetweed
Grand Rapids	2018	*Plantago major*	Broadleaf plantain
Grand Rapids	2018	*Digitaria sanguinalis*	Large crabgrass
Grand Rapids	2018	*Echinochloa crus-galli*	Barnyard grass
Grand Rapids	2018	*Poa pratensis*	Kentucky bluegrass
Grand Rapids	2018	*Portulaca oleracea*	Common purslane
Grand Rapids	2018	*Potentilla simplex*	Oldfield cinquefoil
International Falls	2019	*Chenopodium pratericola*	Desert goosefoot
International Falls	2019	*Ambrosia artemisiifolia*	Common ragweed
International Falls	2019	*Matricaria discoidea*	Pineapple weed
International Falls	2019	*Descurainia sophia*	Herb-sophia
International Falls	2019	*Medicago lupulina*	Black medic
International Falls	2019	*Juncus bufonius*	Toad rush
International Falls	2019	*Juncus dudleyi*	Dudley's rush
International Falls	2019	*Juncus spp.*	Unknown rush1
International Falls	2019	*Juncus tenuis*	Path rush
International Falls	2019	*Plantago major*	Broadleaf plantain
International Falls	2019	*Veronica peregrina*	Purslane speedwell
International Falls	2019	*Sporobolus vaginiflorus*	Poverty dropseed
International Falls	2019	*Digitaria ischaemum*	Smooth crabgrass
International Falls	2019	*Festuca trachyphylla*	Hard fescue
Marshall	2018	*Lactuca serriola*	Prickly lettuce
Marshall	2018	*Coronopus didymus*	Lesser swinecress
Marshall	2018	*Euphorbia spp.*	Spurge
Marshall	2018	*Trifolium repens*	White clover
Marshall	2018	*Fraxinus americana*	White ash
Marshall	2018	*Oxalis spp.*	Wood-sorrel
Marshall	2018	*Sporobolus vaginiflorus*	Poverty dropseed
Marshall	2018	*Digitaria ischaemum*	Smooth crabgrass
Marshall	2018	*Digitaria sanguinalis*	Large crabgrass
Marshall	2018	*Polygonum aviculare*	Prostrate knotweed
Marshall	2018	*Portulaca oleracea*	Common purslane
Roseville	2018	*Sambucus racemosa*	Red elderberry
Roseville	2018	*Chenopodium album*	Common lambsquarter
Roseville	2018	*Ambrosia artemisiifolia*	Common ragweed
Roseville	2018	*Conyza canadensis*	Horseweed
Roseville	2018	*Cirsium arvense*	Canadian thistle
Roseville	2018	*Taraxacum officinale*	Dandelion
Roseville	2018	*Medicago lupulina*	Black medic
Roseville	2018	*Mollugo verticillata*	Carpetweed
Roseville	2018	*Oxalis spp.*	Wood-sorrel
Roseville	2018	*Plantago major*	Broadleaf plantain
Roseville	2018	*Sporobolus vaginiflorus*	Poverty dropseed

Research site	Seeding year	Scientific name	Common name
Roseville	2018	*Leptochloa fusca*	Bearded sprangletop
Roseville	2018	*Digitaria ischaemum*	Smooth crabgrass
Roseville	2018	*Digitaria sanguinalis*	Large crabgrass
Roseville	2018	*Setaria glauca*	Yellow foxtail
Roseville	2018	*Setaria viridis*	Green foxtail
Roseville	2018	*Poa pratensis*	Kentucky bluegrass
Roseville	2018	*Polygonum aviculare*	Prostrate knotweed
Roseville	2018	*Portulaca oleracea*	Common purslane
Roseville	2018	*Typha spp.*	Cattail
Roseville	2018	*Urtica dioica*	Stinging nettle
Saint Cloud	2019	*Chenopodium standleyanum*	Woodland goosefoot
Saint Cloud	2019	*Ambrosia artemisiifolia*	Common ragweed
Saint Cloud	2019	*Conyza canadensis*	Horseweed
Saint Cloud	2019	*Coronopus didymus*	Lesser swinecress
Saint Cloud	2019	*Euphorbia maculata*	Spotted spurge
Saint Cloud	2019	*Medicago lupulina*	Black medic
Saint Cloud	2019	*Trifolium repens*	White clover
Saint Cloud	2019	*Juncus dudleyi*	Dudley's rush
Saint Cloud	2019	*Mollugo verticillata*	Carpetweed
Saint Cloud	2019	*Oxalis spp.*	Wood-sorrel
Saint Cloud	2019	*Oxalis stricta*	Common yellow wood-sorrel
Saint Cloud	2019	*Oxalis violacea*	Violet wood-sorrel
Saint Cloud	2019	*Digitaria ischaemum*	Smooth crabgrass
Saint Cloud	2019	*Digitaria sanguinalis*	Large crabgrass
Saint Cloud	2019	*Setaria viridis*	Green foxtail
Saint Cloud	2019	*Polygonum aviculare*	Prostrate knotweed
Saint Cloud	2019	*Portulaca oleracea*	Common purslane
Saint Cloud	2019	*Potentilla argentea*	Silvery cinquefoil
Saint Cloud	2019	*Typha augustifolia*	Narrow-leaf cattail
Saint Cloud	2019	*Verbena bracteata*	Carpet vervain
Willmar	2019	*Amaranthus retroflexus*	Redroot pigweed
Willmar	2019	*Chenopodium album*	Common lambsquarter
Willmar	2019	*Ambrosia artemisiifolia*	Common ragweed
Willmar	2019	*Solidago altissima*	Tall goldenrod
Willmar	2019	*Symphyotrichum ericoides*	White heath aster
Willmar	2019	*Cirsium arvense*	Canadian thistle
Willmar	2019	*Lactuca serriola*	Prickly lettuce
Willmar	2019	*Taraxacum officinale*	Dandelion
Willmar	2019	*Capsella bursa-pastoris*	Shepherd's-purse
Willmar	2019	*Euphorbia maculata*	Spotted spurge
Willmar	2019	*Plantago major*	Broadleaf plantain
Willmar	2019	*Eragrostis cilianensis*	Stinkgrass
Willmar	2019	*Digitaria sanguinalis*	Large crabgrass
Willmar	2019	*Setaria glauca*	Yellow foxtail
Willmar	2019	*Setaria viridis*	Green foxtail
Willmar	2019	*Poa compressa*	Canada bluegrass
Willmar	2019	*Fallopia convolvulus*	Black bindweed
Willmar	2019	*Potentilla argentea*	Silvery cinquefoil
Willmar	2019	*Typha augustifolia*	Narrow-leaf cattail
Worthington	2019	*Matricaria discoidea*	Pineapple weed
Worthington	2019	*Taraxacum officinale*	Dandelion
Worthington	2019	*Capsella bursa-pastoris*	Shepherd's-purse

Research site	Seeding year	Scientific name	Common name
Worthington	2019	*Euphorbia geyeri*	Dune spurge
Worthington	2019	*Euphorbia maculata*	Spotted spurge
Worthington	2019	*Euphorbia serpyllifolia*	Thyme-leaved spurge
Worthington	2019	*Medicago lupulina*	Black medic
Worthington	2019	*Juncus interior*	Inland rush
Worthington	2019	*Oxalis spp.*	Wood-sorrel
Worthington	2019	*Oxalis stricta*	Common yellow wood-sorrel
Worthington	2019	*Eragrostis pectinacea*	Tufted lovegrass
Worthington	2019	*Sporobolus vaginiflorus*	Poverty dropseed
Worthington	2019	*Digitaria ischaemum*	Smooth crabgrass
Worthington	2019	*Digitaria sanguinalis*	Large crabgrass
Worthington	2019	*Setaria viridis*	Green foxtail
Worthington	2019	*Lolium perenne*	Perennial ryegrass
Worthington	2019	*Poa pratensis*	Kentucky bluegrass
Worthington	2019	*Portulaca oleracea*	Common purslane