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A Greenhouse Study of Concrete Grinding Residue Influences on Seedling Emergence and Early Growth of Selected Prairie Species

Chenyi Luo
Beijing University of Chinese Medicine

Zhuangji Wang
United States Department of Agriculture

Farnaz Kordbacheh
University of Manitoba

See next page for additional authors

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Abstract

Concrete grinding residue (CGR) is a byproduct of diamond grinding, a road surface maintenance technique. Direct deposition of CGR along roadsides may influence plant growth, which has not been fully studied. Particularly, systematic experiments of CGR effects on selected common prairie species growth under controlled environments are rarely reported. Thus, in this study, a greenhouse experiment was performed to determine CGR effects on seedling emergence and aboveground biomass for four roadside prairie species: Indian grass, Canada wild rye, partridge pea, and wild bergamot. Nicollet loam and Hanlon fine sandy loam were used, and CGR of 4 rates, 0, 2.24, 4.48, and 8.96 kg m−2, were applied in two ways, either mixed with the soil or applied on the soil surface. Multiple comparisons indicate that CGR produced mixed impacts on seedling emergence, depending on plant species, while aboveground biomass is not significantly influenced by CGR in general. ANOVA analysis with stepwise linear regression indicates that CGR had no uniform effects on seedling emergence, and CGR impacts should be studied for specific plant species and soil types. In conclusion, while CGR may lead to negative environmental issues on roadside plants depending on the plant species and soil types, if aboveground biomass is a major consideration, CGR effects are negligible. This study provides reference information for regulating CGR depositions along roadsides. Future studies may focus on investigating the relationship between CGR effects on seedling emergence and species succession in actual roadside environments.

Keywords

Concrete grinding residue (CGR), Greenhouse experiment, Seedling emergence, Aboveground biomass

Disciplines

Agronomy and Crop Sciences | Civil and Environmental Engineering

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Authors

Chenyi Luo, Zhuangji Wang, Farnaz Kordbacheh, Shengting Li, Bora Cetin, Halil Ceylan, and Robert Horton

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Chenyi Luo · Zhuangji Wang · Farnaz Kordbacheh · Shengting Li · Bora Cetin · Halil Ceylan · Robert Horton

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Abstract Concrete grinding residue (CGR) is a byproduct of diamond grinding, a road surface maintenance technique. Direct deposition of CGR along roadsides may influence plant growth, which has not been fully studied. Particularly, systematic experiments of CGR effects on selected common prairie species growth under controlled environments are rarely reported. Thus, in this study, a greenhouse experiment was performed to determine CGR effects on seedling emergence and aboveground biomass for four roadside prairie species: Indian grass, Canada wild rye, partridge pea, and wild bergamot. Nicollet loam and Hanlon fine sandy loam were used, and CGR of 4 rates, 0, 2.24, 4.48, and 8.96 kg m^{-2}, were applied in two ways, either mixed

Core Ideas (a) A greenhouse experiment was performed to study concrete grinding residue (CGR).
(b) CGR effects on seedling emergence and 60-day aboveground plant biomass were studied.
(c) The effects of CGR on seedling emergence depended on plant species.
(d) CGR produced no significant effects on 60-day aboveground plant biomass.

C. Luo
School of Life Sciences, Beijing University of Chinese Medicine, Beijing 102488, China

Z. Wang
Adaptive Cropping System Laboratory, USDA-ARS, Beltsville, MD 20705, USA

Z. Wang (✉)
Department of Plant Science & Landscape Architecture, University of Maryland, College Park, MD 20742, USA
e-mail: cauwzj@gmail.com

F. Kordbacheh
Department of Plant Science, University of Manitoba, Winnipeg R3T 2N2, Canada

S. Li (✉)
Key Laboratory of Transport Industry of Road Structure and Material, Ministry of Transport, Research Institute of Highway, Beijing 100088, China
e-mail: st.li@rioh.cn

B. Cetin
Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI 48824, USA

H. Ceylan
Department of Civil, Construction and Environmental Engineering and Program for Sustainable Pavement Engineering and Research (PROSPER) at Institute for Transportation (InTrans), Iowa State University, Ames, IA 50011, USA

R. Horton
Department of Agronomy, Iowa State University, Ames, IA 50011, USA

with the soil or applied on the soil surface. Multiple comparisons indicate that CGR produced mixed impacts on seedling emergence, depending on plant species, while aboveground biomass is not significantly influenced by CGR in general. ANOVA analysis with stepwise linear regression indicates that CGR had no uniform effects on seedling emergence, and CGR impacts should be studied for specific plant species and soil types. In conclusion, while CGR may lead to negative environmental issues on roadside plants depending on the plant species and soil types, if aboveground biomass is a major consideration, CGR effects are negligible. This study provides reference information for regulating CGR depositions along roadsides. Future studies may focus on investigating the relationship between CGR effects on seedling emergence and species succession in actual roadside environments.

Keywords Concrete grinding residue (CGR) · Greenhouse experiment · Seedling emergence · Aboveground biomass

1 Introduction

Diamond grinding is commonly used for concrete road surface maintenance to improve vehicle riding quality, reduce road noise, enhance skid resistance, and extend road service life (Mosher 1985; ACPA 1997; Defrain 1989). Concrete grinding residue (CGR) is a slurry-type byproduct of diamond grinding containing concrete particles mixed with water (Goodwin and Roshek 1992; Druschel et al. 2012). CGR waste treatments vary among states, but in the Midwestern US region, it is common to directly deposit CGR along roadsides. That may cause environmental risks to roadside soils and plants (Druschel et al. 2012; Wingeyer et al. 2018; Luo et al. 2019).

The effects of CGR on the roadside environment were studied based on CGR chemical composition and the induced changes in soil chemical and physical properties. For example, DeSutter et al. (2011b), Yonge and Shanmugam (2005), Hanson et al. (2010), Yang et al. (2019), and Ceylan et al. (2019) reported that the CGR pH value could be as high as 12, elevating the soil pH by 1.2~2.0. Wingeyer et al. (2018) reported that the effective calcium carbonate equivalent values of CGR sampled from Nebraska were as much as 28.1%, and Yang et al. (2019) reported that the electrical conductivity values of CGR were up to 13.7 dS m^{-1}. CGR only had transient effects in raising soil electrical conductivity (EC) and K, Na, Mg, and Ca concentrations. However, such effects could spread from the CGR deposit areas to the whole roadside soil area. For example, Yang et al. (2020) reported that when CGR was deposited within a 1.5-m roadside strip immediately next to the road, changes in Ca and Na concentrations, as well as soil CEC, ESP, and PBS, were detected in external roadside areas. Caltrans (1997) and DeSutter et al. (2011b) comprehensively investigated inorganic toxic elements (e.g., As, Ba, Cd, Cr, Hg, Pb) and organic toxic components (e.g., benzene, toluene, ethylbenzene, xylene, polynuclear aromatic hydrocarbons) within CGR. However, CGR exhibited limited or no hazardous characteristics, similar to that for the concrete exposed to traffic and construction activities (Kluge et al. 2018). Reported CGR effects on soil physical properties have in general been small. For example, Luo et al. (2019) reported insignificant CGR effects on soil bulk density, saturated hydraulic conductivity, and soil infiltrability from their 1-year controlled field study; Wingeyer et al. (2018) demonstrated that CGR did not increase roadside water runoff. DeSutter et al. (2011b) reported an increase in saturated hydraulic conductivity for one of their CGR application rates. However, the soil samples in their study were disturbed and CGR was fully mixed with soil, which reduced its representativeness to actual roadside conditions, where CGR slurry was deposited on the soil surface.

Growing prairie plant species along roadsides provides two benefits: (1) partial removal of automobile exhaust and highway runoff pollutants (Kaighn and Yu 1996; Deshmukh et al. 2019) and (2) “marginal habitats” for pollinators, e.g., ground-nesting bees or butterflies (Ries et al. 2001; Hopwood 2008). However, roadside prairie plants can also serve as a path for species invasion (Milton et al. 2015). Thus, due to the local environmental and ecological significance of roadside areas, it is critical to monitor the dynamics of roadside plant growth.

Roadside plant growth could be affected by CGR deposition. However, CGR impacts varied according to the experimental setting and the plant species. In a greenhouse study on *Bromus inermis* L. (smooth bromegrass), DeSutter et al. (2011a) found that 8% CGR, based on soil dry mass, significantly promoted early stage (90-day) shoot biomass, while 25% CGR did not benefit shoot growth compared with non-CGR results.

The reasons for such a discrepancy could be due to CGR-elevated soil pH and EC values, and the induced changes of root ion uptake patterns, such as Ca. However, it was reported that between the two CGR rates, the concentration of toxic elements (e.g., Ba, Cd, Co, Cr, Hg, Pb, Sr) in plant tissues was not significantly different, even though some significant differences were detected within the soil. In contrast, Luo et al. (2019) and Wingeyer et al. (2018) reported insignificant CGR impacts on aboveground biomass composed of a mixture of prairie species in their controlled field study.

Compared with studies investigating the impact of CGR on soil physical and chemical properties, research results related to the response of plant growth to CGR deposition is limited. One difficulty in investigating CGR impacts on plant growth is that plant growth can be highly affected by weather and soil conditions, such that the CGR effects may be hidden (Wingeyer et al. 2018; Luo et al. 2019). Although experiments under relatively controlled environments, such as greenhouse, were performed (DeSutter et al. 2011a), only limited numbers of species were tested, in contrast to the numbers of species and functional groups found along roadsides (Wingeyer et al. 2018; Ament et al. 2017). More importantly, seedling emergence under CGR effects, which also provides basic information on the early growth and compositional changes in the plant community, has not yet been reported. Thus, performing a greenhouse study to measure the impacts of CGR on seedling emergence of selected roadside prairie species under multiple CGR rates will enhance our understanding of CGR impacts on early plant growth and provide detailed information with respect to each specific plant species.

The objective of this study was to perform a controlled greenhouse experiment to determine the effects of CGR on the emergence rate and early growth of aboveground biomass for four common prairie plant species. This study was a direct extension of an earlier greenhouse study by DeSutter et al. (2011a). The CGR rates matched those used by Luo et al. (2019) in their field study. The plant species were selected based on MnDOT seed mixture component requirements (http://docs.mncia.org/public/fieldservices/MnDOT_State_Seed_Mix_Acceptable_Substitution_Table.pdf), which could also represent the plant functional groups found in the Luo et al. (2019) field experiment. Such experimental settings established a direct comparison between greenhouse results and the field results reported in Luo et al. (2019).

2 Materials and Methods

The greenhouse experiment was performed in the Agronomy Greenhouse of Iowa State University. *Sorghastrum nutans* L. (Indian grass), *Elymus canadensis* L. (Canada wild rye), *Chamaecrista fasciculata* Michx. (partridge pea), and *Monarda fistulosa* L. (wild bergamot) were the four species selected for this study, because (1) they represented common prairie species found along roadsides; (2) each of them represented a functional group: warm-seasoned grass, cool-seasoned grass, leguminous forbs, and non-leguminous forbs, respectively; (3) the two forbs could serve critical roles in supporting native pollinators (Bonin and Tracy 2011; Kordbacheh et al., unpublished manuscript), while the two kinds of grass could reduce sediment/pollutants from surface runoff (Helmers et al. 2012; Zhou et al. 2014); and (4) the responses of those four species to CGR had not been fully studied previously. Prior to the greenhouse experiment, the seed germinability of each prairie species was tested under optimal conditions in the Seed Science Center of Iowa State University. Germination rates of *S. nutans*, *E. canadensis*, *C. fasciculata*, and *M. fistulosa* were 36%, 96%, 28%, and 16%, respectively.

CGR was obtained from a diamond grinding project located at 6078-6216 McAndrews Road, in Apple Valley, MN. The gravimetric water content (θ_m) of the CGR slurry was 0.54 g g^{-1}. The CGR solid portion consisted of 39% sand, 53% silt, and 8% clay. In the greenhouse study, CGR was applied at four rates: A = 0 kg m^{-2}, B = 2.24 kg m^{-2}, C = 4.48 kg m^{-2}, and D = 8.96 kg m^{-2}, based on its dry mass. Two application methods were used. One was to uniformly mix CGR with the soil (MIX, hereafter), and the other one was to apply CGR directly on the soil surface (SUR, hereafter). Nicollet loam (fine loamy, mixed, superactive, mesic Aquic Hapludolls) and Hanlon fine sandy loam (coarse loamy, mixed, superactive, mesic Cumulic Hapludolls) were the two soil types used in this experiment, because their textures were similar to the soil at the Minnesota roadside (the texture analysis results of roadside soil were omitted for simplicity). The soils were air-dried, crushed, and passed through a 0.002-m sieve.

The greenhouse experiment was performed using plastic pots of 10 cm in diameter and 10 cm in height. In each pot, the dry mass of the CGR-soil mixtures was 500 g. For MIX applications, air-dried soil and CGR slurry were mixed by hand for 30 min. Additional distilled water was applied based on the quantity of CGR slurry, such that for each CGR rate, the initial volumetric water content of the CGR-soil mixtures was the same. For SUR applications, the soil was directly placed into the pots, such that for each CGR rate, the soil dry mass for both application methods were equal. Soil water content in SUR applications was also adjusted to achieve similar initial soil conditions in both MIX and SUR applications.

Twenty-five seeds were planted uniformly within each pot. In MIX applications, CGR-soil mixtures were watered to field capacity before seeding. For *M. fistulosa*, the sowing depth was approximately 0.5 cm, while for other species, the planting depth was about 1 cm. In SUR applications, soils were first watered to field capacity, and seeds were planted. Then, CGR was placed uniformly on the soil surface at specified rates. A combination of 7 treatments, including MIX/SUR application methods and 4 proposed CGR rates, was applied to each prairie species and soil type, since the 0-kg m^{-2} CGR treatment was the same for MIX and SUR applications.

Pots were placed in the greenhouse for 60 days to record seedling emergence. The greenhouse temperature was maintained at 22 °C during daytime and 18 °C during nighttime with no lighting source in addition to natural solar radiation. Pots were watered daily with 50–100 ml water to maintain the soil moisture. The number of emerged seedlings was recorded each day before watering. After the 60-day period, the aboveground vegetation was clipped and oven-dried in paper bags at 65°C for 4 days (García et al. 1993) to obtain the biomass.

3 Results and Discussion

3.1 Multiple Comparison Results

Multiple comparison models were used to investigate the responses of seedling emergence and aboveground biomass to CGR rates and application methods for each species.

The measured results are presented in Table 1. In the left-side portion of Table 1, we compared the 60-day seedling emergence rates among the 4 CGR rates and 4 prairie species. For Nicollet loam, except for *E. canadensis* in the MIX and SUR applications and *C. fasciculata* in the SUR application, CGR deposition rates produced no significant influences on the seedling emergence. For *E. canadensis* in the MIX and SUR applications, the largest emergence rates occurred at the 4.48-kg m^{-2} CGR treatment, and a higher CGR rate, i.e., 8.96 kg m^{-2}, did not benefit seedling emergence, while for *C. fasciculata* in the SUR application, the largest emergence rate was achieved at the 2.24 kg m^{-2} CGR rate, and no significant differences were shown among other CGR rates. Multiple comparisons of the actual mean (species) emergence rates (the heart symbol in Table 1) revealed significant differences among the 4 prairie species; however, if normalized by the pre-tested germination rates, the relative mean (species) emergence rates (the club symbol in Table 1) presented insignificant differences. Thus, the type of prairie species was the major factor associated with differences in the emergence rates. The relative mean (CGR) emergence rates (the spade symbol in Table 1) were the averages of relative emergence rates for each CGR rate. However, the actual emergence rates could not be averaged directly due to the significant differences among the 4 prairie species. The insignificant differences shown in the relative mean (CGR) for both the MIX application and the SUR application implied, in an averaged sense, that CGR deposition did not impact the seedling emergence when the soil type was Nicollet loam.

For Hanlon fine sandy loam, the emergence results were similar to those for Nicollet loam. Significant differences only occurred in *E. canadensis* for the MIX and SUR applications and in *S. nutans* for the MIX application, and the patterns of multiple comparison results of actual mean and relative mean (species) were about the same as the ones shown in Nicollet loam. However, in Hanlon fine sandy loam, some variations in relative emergence rates occurred among the 4 CGR rates, leading to significant differences in relative mean (CGR) values, which were not consistent with the results for Nicollet loam.

In this experiment, the results indicated that CGR did not influence either the actual or the relative seedling emergence of *M. fistulosa* for the selected CGR rates, soil types, and application methods. However, CGR did affect seedling emergence of *E. canadensis* for both soil types and application methods. For the other two species, *S. nutans* and *C. fasciculata*, CGR effects on seedling emergence were dependent on soil types and/or application methods. For example, *S. nutans* responded to CGR application in Hanlon fine sandy

Table 1

		60-day Emergence Rate (Actual/Relative)◇				Relative Means (CGR)♠	60-day Aboveground Biomass (g)			
Plant Species		*Chamaecrista fasciculata* Michx.	*Elymus canadensis* L.	*Sorghastrum nutans* L.	*Monarda fistulosa* L.		*Chamaecrista fasciculata* Michx.	*Elymus canadensis* L.	*Sorghastrum nutans* L.	*Monarda fistulosa* L.
Nicollet Loam, MIX Application										
CGR Rate	0 kg m^{-2}	0.10/0.36a	0.06/0.06a	0.06/0.17a	0.06/0.38a	0.24a	0.61a	0.09a	0.54a	0.07a
	2.24 kg m^{-2}	0.07/0.25a	0.30/0.31b	0.07/0.19a	0.00/0.00a	0.19a	0.26a	0.46a	0.04a	0.00a
	4.48 kg m^{-2}	0.09/0.32a	0.59/0.61c	0.09/0.25a	0.02/0.13a	0.33a	0.14a	1.18a	0.02a	0.00a
	8.96 kg m^{-2}	0.10/0.36a	0.26/0.27b	0.02/0.06a	0.02/0.13a	0.21a	0.18a	0.76a	0.01a	0.00a
Actual Means ♥		0.09b	0.3c	0.06ab	0.03a		0.3a	0.62b	0.15a	0.02a
Relative Means (Species) ♣		0.32a	0.35a	0.16a	0.15a					
Nicollet Loam, SUR Application										
CGR Rate	0 kg m^{-2}	0.10/0.36a	0.06/0.06a	0.06/0.17a	0.06/0.38a	0.24a	0.61a	0.09a	0.54a	0.07a
	2.24 kg m^{-2}	0.29/1.04b	0.35/0.36bc	0.16/0.44a	0.12/0.75a	0.65a	2.43a	0.64a	0.57a	0.01a
	4.48 kg m^{-2}	0.11/0.39a	0.48/0.50c	0.10/0.28a	0.12/0.75a	0.48a	0.76a	0.62a	0.19a	0.00a
	8.96 kg m^{-2}	0.15/0.54ab	0.19/0.20ab	0.08/0.22a	0.03/0.19a	0.29a	0.67a	0.27a	0.22a	0.00a
Actual Means ♥		0.16b	0.27c	0.1ab	0.08a		1.12b	0.41a	0.38a	0.02a
Relative Means (Species) ♣		0.58a	0.28a	0.28a	0.51a					
Hanlon Fine Sandy Loam, MIX Application										
CGR Rate	0 kg m^{-2}	0.08/0.27a	0.13/0.14a	0.11/0.31ab	0.04/0.25a	0.24ab	0.44a	0.24a	0.25a	0.0740a
	2.24 kg m^{-2}	0.03/0.11a	0.29/0.30b	0.18/0.50b	0.01/0.06a	0.24b	0.11a	0.40a	0.11a	0.0003a
	4.48 kg m^{-2}	0.02/0.07a	0.09/0.09a	0.04/0.11a	0.02/0.13a	0.11a	0.10a	0.29a	0.05a	0.1860a
	8.96 kg m^{-2}	0.06/0.21a	0.23/0.24ab	0.03/0.08a	0.05/0.31a	0.21ab	0.19a	0.44a	0.03a	0.0010a
Actual Means ♥		0.05ab	0.19c	0.09b	0.03a		0.21bc	0.34c	0.11ab	0.07a
Relative Means (Species) ♣		0.17a	0.19a	0.25a	0.19a					
Hanlon Fine Sandy Loam, SUR Application										
CGR Rate	0 kg m^{-2}	0.08/0.29a	0.13/0.14ab	0.11/0.31a	0.04/0.25a	0.24b	0.44a	0.24a	0.25a	0.0740c
	2.24 kg m^{-2}	0.07/0.25a	0.31/0.32c	0.10/0.28a	0.04/0.25a	0.28b	0.40a	0.48a	0.34a	0.0005b
	4.48 kg m^{-2}	0.14/0.50a	0.26/0.27bc	0.03/0.08a	0.00/0.00a	0.21b	1.81a	0.39a	0.15a	0.0000a
	8.96 kg m^{-2}	0.00/0.00a	0.07/0.07a	0.01/0.03a	0.00/0.00a	0.03a	0.00a	0.21a	0.04a	0.0000a
Actual Means ♥		0.07b	0.19c	0.06ab	0.02a		0.66b	0.33ab	0.20a	0.02a
Relative Means (Species) ♣		0.26a	0.2a	0.17a	0.13a					

◇ The "Relative Emergence Rate" indicates the ratios between the actual emergence rates and the germination rates measured in Iowa State University Seed Science Center; ♠ The "Relative Means (CGR)" indicates the means of relative emergence rate, for each CGR application rate; ♥ The "Actual Means" indicates the means of actural measured emergence rate or aboveground biomass, for each plant species; ♣ The "Relative Means (Species)" indicates the means of relative emergence rate, for each plant species loam for the MIX application, while *C. fasciculata* was influenced in Nicollet loam for the SUR application. In general, relatively low CGR rates promoted seedling emergence, while emergence rates were not benefited at higher CGR rates.

The differences in relative mean (CGR) between the two soil types might be due to the interaction between CGR and soils. To seek better understand of this, soil pH and EC values were measured after the greenhouse experiment, and the results are presented in Fig. 1 (the procedures of EC measurements were presented in the Appendix). While the trends of soil EC variations with respect to CGR rates were similar for the two soil types, the soil pH values in Nicollet loam were about 0.5 smaller than the values in Hanlon fine sandy loam. Especially for the SUR application in Nicollet loam, pH in upper and lower half layers had relatively small values compared with the pH in the MIX application, corresponding to a relatively slow redistribution pattern of alkaline ions. This is a possible reason that CGR effects on the relative mean (CGR) were different between the two selected soil types. Physical resistance produced by the CGR layers in SUR application could be another factor that reduced the emergence rates; however, it was not the most critical factor, because the relative mean (CGR) value for Hanlon fine sandy loam with 8.96 kg m^{-2} CGR rate was the only datum that possibly reflected such physical resistance.

In the right-side portion of Table 1, we compared the 60-day aboveground biomass among the 4 CGR rates and 4 species. The only significant differences among the 4 CGR rates occurred for *M. fistulosa* in Hanlon fine sandy loam for the SUR application; however, in that case, the absolute values of the aboveground biomass were small. For the other cases, insignificant differences induced by CGR applications among the 4 species were observed.

Compared with the seedling emergence results, the variations of aboveground biomass with respect to CGR rates were relatively small from the perspective of statistical significance. One possible reason was that for the species with a relatively small emergence rate, the emerged plants could have large biomass due to the lack of inter-plant competition; however, a relatively large seedling emergence could correspond to the significant inter-plant competition. Thus, there was some potential compensation mechanism causing the aboveground biomass data to be relatively uniform. The aboveground biomass results were consistent with the controlled field experiments reported by Luo et al. (2019), although the growing stage of the prairie was different in this study. DeSutter et al. (2011a) claimed that CGR could lead to significant impacts on the 90-day biomass of *B. inermis*. However, we did not observe this effect on the prairie species tested in this study. Our results demonstrated that investigating the emergence rate could be more effective than investigating the aboveground biomass for elucidating the impact of CGR on the seedlings.

3.2 General Remarks on the Emergence Results

Because for each prairie species, the responses of seedling emergence to CGR rates, application methods, and soil types were relatively complicated, an ANOVA model that included all of the factors and results was used to provide a more comprehensive understanding of the dependence between seedling emergence and external conditions. Combined with the ANOVA, a stepwise regression analysis was used to identify the most critical factors that significantly influenced the seedling emergence results. The results of feature selection via stepwise regression are given in Eq. (1),

$$\mathrm{ER} = \mathrm{CGR} \times \mathrm{Ps} + \mathrm{Ps} \times \mathrm{App} + \mathrm{CGR} \times \mathrm{Soil} + \mathrm{Ps} \times \mathrm{Soil} \tag{1}$$

In Eq. (1), “ER” indicates the emergence rate; "CGR" represents the CGR rate; “Ps” represents plant species; “App” indicates MIX or SUR application methods; and “Soil” represents the two selected soil types. The results of this analysis are presented in Table 2. Only the critical factors with $p < 0.05$ are shown. *M. fistulosa*, with 8.96-kg m^{-2} CGR rates with MIX application in Hanlon fine sandy loam was taken as the reference level in the linear model.

The main effects of the four input factors, CGR, Ps, App, and Soil, were not selected in the linear model, but the effects of CGR were expressed in the interactions with Ps and Soil. This implied that CGR rates did not have uniform impacts on seedling emergence among the selected plant species and soils. In turn, the CGR effects must be identified for specific species and soil type. For *M. fistulosa*, the application method affected the emergence rate, possibly due to the physical resistance of the surface applied CGR, since the seedlings of this species were relatively small compared with that for the other species. Two other significant interactions occurred between soil types and prairie species, which represented

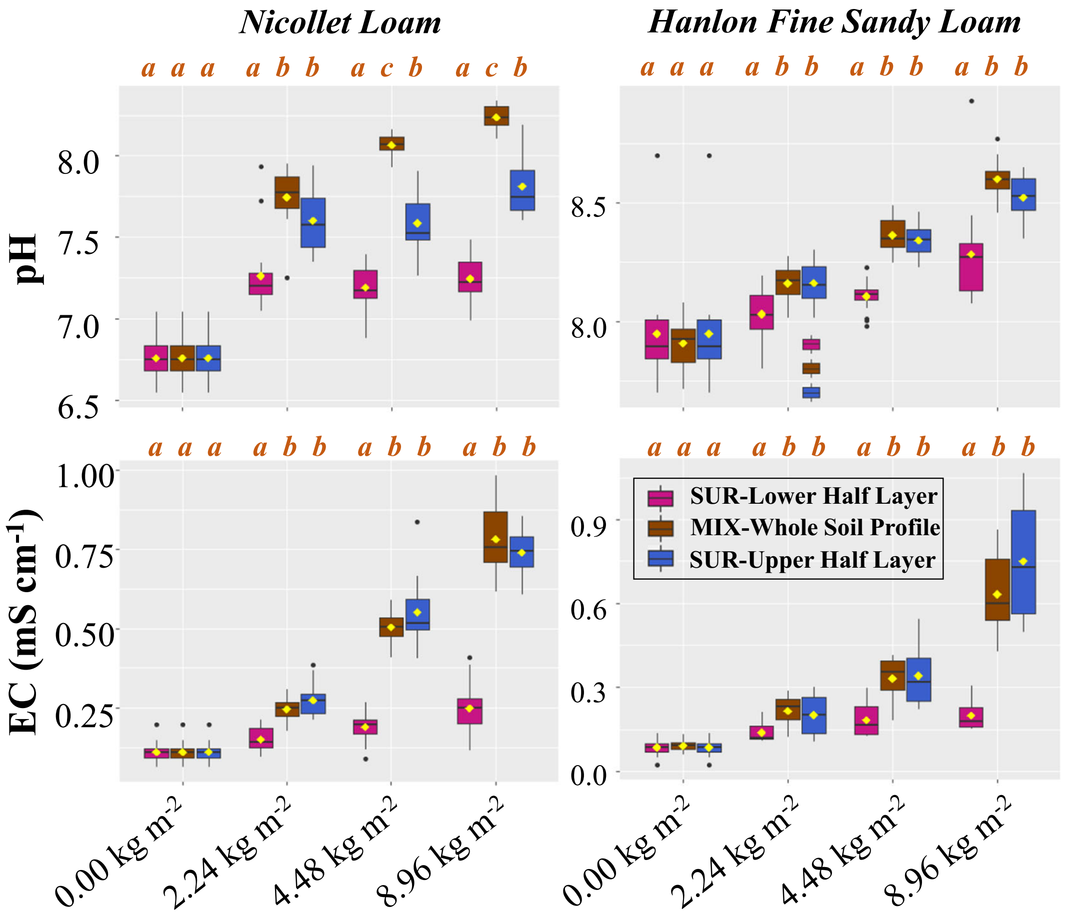

Fig. 1 Variations of pH and electrical conductivity (EC) values with respect to CGR rates and application methods (MIX or SUR) are shown. The results of multiple comparisons are included. The mean values of soil pH and EC are indicated with yellow diamonds

the effects of soil type on the seedling emergence of *C. fasciculata* and *M. fistulosa*.

4 Summary

A greenhouse experiment was performed to investigate the effects of concrete grinding residue (CGR) slurry on seedling emergence and early growth (60-day aboveground biomass) on 4 common prairie plant species: *S. nutans*, *C. fasciculata*, *E. canadensis*, and *M. fistulosa*. CGR of 4 rates, 0, 2.24, 4.48, and 8.96 kg m^{-2}, was either mixed with (MIX) or surface applied (SUR) to both Nicollet loam and Hanlon fine sandy loam. The seedling emergence and 60-day aboveground plant biomass values were measured. Multiple comparisons were used for data analysis, and an ANOVA model with stepwise linear regression was used to identify critical factors that impacted the seedling emergence. Although CGR showed some significant effects on seedling emergence, these effects were dependent on specific plant species and soil types. Thus, in practice, CGR had mixed effects on seedling emergence. However, for the early stage aboveground biomass, CGR effects were insignificant, in general.

Thus, for roadside CGR depositions, if plant biomass is the primary consideration, CGR impacts can be neglected. However, CGR application can potentially change the plant community composition because of CGR species-specific effects on seedling emergence, and such changes could trend toward a specific plant species that is either more beneficial for pollinators or more useful in terms of controlling highway runoff and removing sediments. Therefore, ecological and environmental impacts of the roadside plant community due to

Table 2

Factor	*p*-value
CGR Rate (kg m^{-2}) × Plant Species	
0.00 × *Elymus canadensis* L.	<0.0001
2.24 × *Elymus canadensis* L.	<0.0001
4.48 × *Elymus canadensis* L.	<0.0001
8.96 × *Elymus canadensis* L.	<0.0001
0.00 × *Sorghastrum nutans* L.	<0.0001
2.24 × *Sorghastrum nutans* L.	<0.0001
4.48 × *Sorghastrum nutans* L.	0.0003
8.96 × *Sorghastrum nutans* L.	0.009
0.00 × *Chamaecrista fasciculata* Michx.	<0.0001
2.24 × *Chamaecrista fasciculata* Michx.	0.0003
4.48 × *Chamaecrista fasciculata* Michx.	0.001
8.96 × *Chamaecrista fasciculata* Michx.	0.001
0.00 × *Monarda fistulosa* L.	0.003
Plant Species × Application Method	
Monarda fistulosa L. × SUR	0.016
CGR Rate (kg m^{-2}) × Soil Type	
4.48 × Nicollet Loam	0.033
8.96 × Nicollet Loam	0.048
Plant Species × Soil Type	
Chamaecrista fasciculata Michx. × Nicollet Loam	0.028
Monarda fistulosa L. × Nicollet Loam	0.017

CGR applications must be considered. In addition, the plant response to CGR is also context-dependent, such that it can be modified via changing the type of prairie species, soil types, and the CGR application methods.

This study provides reference information and guidelines for the impacts of CGR deposition, which can lead to best management practices for protecting the roadside ecosystem and environment. Because the greenhouse condition is different from real roadside conditions, e.g., weather and soil structure, future roadside studies are needed to (1) validate the greenhouse results and (2) investigate long-term CGR effects on species reconfiguration.

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Compliance with Ethical Standards

Disclaimer Endorsement by MnDOT and Minnesota LRRB is not implied and should not be assumed. This paper does not constitute a standard, specification, or regulation.

Appendix

For reference, soil pH and EC in each pot were measured after the greenhouse experiment, and the results are included in this appendix. For the MIX treatments, one sample was prepared for each pot, while for the SUR treatments, the soil profile was divided horizontally into two layers of equal mass after the CGR portion was removed, and the upper and lower soil layers were sampled separately. pH and EC values were measured by 1:1 water extraction via a HI-4522 pH/EC meter

(Hanna Instruments, Woonsocket, RI, USA). The measured results are presented in Fig. 1. DeSutter et al. (2011a) provided a comprehensive analysis of ion concentrations. However, in this study, it is sufficient to present pH and EC values, since K, Na, Mg, and Ca are the most abundant elements in CGR, and the concentrations of trace metals in CGR are relatively small.

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