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Smooth Brome (*Bromus inermis* Leyss) and Soil Chemical Response to Concrete Grinding Residue Application

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Abstract Concrete grinding residue (CGR) is a by-product created by concrete pavement maintenance operations. The application of CGR to roadside soils is not consistently regulated by state agencies across the USA, which is partially due to the lack of science-based information on its impacts to soils and plants. The objectives of this research were to determine the impact of CGR additions to soil on both smooth brome (*Bromus inermis* L.) biomass and plant and soil chemical parameters. In a greenhouse study, two soils were treated with two CGR by-products at 8% and 25% by weight. Shoot biomass was significantly influenced by the main effects (Soil, CGR, and Rate) and by all two-way interactions, but not consistently positively or negatively correlated. Trace metal concentrations in the shoot biomass were variable, but 68% of these metals

had the same concentration or lower in the 25% CGR treatments compared with the controls. Soil pH and electrical conductivity were significantly influenced by the main effects and two-way interactions of Soil × Rate and CGR × Rate, and soil pH was significantly greater in the CGR-treated soils. Calcium, Na, Mg, Al, and S concentrations in soils were all influenced by additions of CGR, but trace metal levels in the treatments were all within the range for uncontaminated soils. Ecosystem impact of applying CGR will be dependent upon the quality of CGR and soil characteristics. Controlling the liming potential of CGR should be considered a best management practice.

Keywords Concrete disposal · Industrial by-product · Roadside soil

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Abbreviations

| | |
|-------|---------------------------------------|
| 10/CA | California interstate highway 10 site |
| 94/MN | Minnesota interstate highway 94 |
| CGR | Concrete grinding residue |
| DOY | Day of year |
| EC | Electrical conductivity |

1 Introduction

Diamond grinding of highway surfaces improves ride, extends useful highway life, and produces a by-product termed concrete grinding residue (CGR; DeSutter et al. 2011). Regulations addressing CGR differ across states

within the USA. Oftentimes, CGR is allowed to be distributed onto roadside soils next to the point of grinding (B. Darr, personal communication, 2010, North Dakota Department of Transportation, USA). In contrast, California requires that CGR be contained in storage ponds or class II landfills (T. Pyle, personal communication, 2010, California Department of Transportation, USA). Recently, Nebraska announced plans to require a permit for land application of CGR (Nebraska Department of Environmental Quality 2010; note: the permit was still under review at the time this publication went to press). The costs for disposal of CGR will vary, but ultimately these costs are forwarded to taxpayers.

Even though diamond grinding is routinely done, little research has characterized the environmental impacts of CGR on soils and plants. The two most recent studies are DeSutter et al. (2011) and Shanmugam (2004). Both studies highlight the characterization of solution and solid phases of CGR for inorganic and organic constituents. Concentrations of trace elements were variable across sampling locations in DeSutter et al. (2011) and likely depended on the composition of the concrete and quality of water used for grinding. Addition of fly/bottom ash or slag to concrete mixtures would also increase variability between sites (Bertolini et al. 2004; Ferreira et al. 2003; Mroueh et al. 2001; Papayianni and Anastasiou 2010). No polynuclear aromatic hydrocarbons were found, but application of high rates of CGR to soils increased water infiltration (DeSutter et al. 2011).

Alteration of soil pH from CGR material addition is likely, which is a concern highlighted by Shanmugam (2004) and the Nebraska Department of Environmental Quality (2010) document. This concern is supported by the elevated pH of the CGR slurry, which ranged from 11.6 to 12.5 in the DeSutter et al. (2011) study and about 12 in the Shanmugam (2004) study. The liming potential of CGR is evidenced by the range of soil pH values measured in non-impacted areas (6.3 to 7.5) and comparing these values with areas that received CGR slurry (7.6 to 9.4; Shanmugam 2004).

There is a lack of science-based information about the impacts of CGR on soil chemistry and plant quality, which justifies the need for additional research to evaluate these potential impacts of CGR. The objectives of this research were to determine the impact of adding CGR to soils on (1) smooth brome (*Bromus inermis* Leyss) growth and elemental con-

centrations in its biomass and (2) changes to soil chemical parameters. Smooth brome grass is a non-native species that has been commonly seeded in roadside areas across the USA and Canada (D. Kirby, personal communication, 2010); therefore, it was chosen to be an indicator of CGR on plant health.

2 Materials and Methods

2.1 Soil and Concrete Grinding Residue

The two soils (0 to 15 cm depths) used for a greenhouse study were a Fargo silty clay (Fine, smectitic, frigid Typic Epiaquerts) and Wyndmere fine sandy loam (course-loamy, mixed, superactive, frigid Aeric Calciaquolls), which were obtained near Fargo, ND, USA (46.86° N, 96.85° W) and the Albert K. Ekre Grassland Preserve in southeast North Dakota (46.55° N, 97.12° W), respectively. The Fargo silty clay was collected from a construction site where the soil was used to improve an interstate highway right-of-way, and the Wyndmere fine sandy loam was collected from an undisturbed, natural area with no known history of cultivation or disturbance. Both soils were air-dried, ground to pass through a stainless steel 2-mm sieve, and stored in low-density polyethylene (LDPE) plastic buckets at 25°C until the treatments were prepared. The physical and chemical characteristics of both soils were determined using standard soil science methodology by the NDSU Soil Testing Laboratory and are reported in Table 1.

Concrete grinding residues were obtained from Interstate-94 in Minnesota (94/MN) and Interstate-10 in California (10/CA), air-dried, and ground to a fine powder using a mortar and pestle. The chemical characteristics of these two concrete grinding residues, relevant to this study, are reported in Table 2. Particle size distributions are reported in DeSutter et al. (2011). The equivalent calcium carbonate (% CaCO₃) and the lime purity (% CaCO₃) were determined by Ward Laboratories (Kearney, NE, USA) and were 27.7 and 34.7, respectively, for the 94/MN and 16.4 and 20.9, respectively, for the 10/CA. The 94/MN and 10/CA had solution phase pH values of 11.8 and 12.5, respectively (DeSutter et al. 2011). The solution phase electrical conductivity (EC) of the 94/MN and 10/CA, converted from total dissolved solids (DeSutter et al. 2011) using the assumption that EC is equivalent to

Table 1 Chemical and physical characteristics of the Wyndmere fine sandy loam and the Fargo silty clay soils

| Soil | Sand g kg ⁻¹ | Silt g kg ⁻¹ | Clay g kg ⁻¹ | pH ^a | EC ^b dS m ⁻¹ | OM ^c g kg ⁻¹ | NO ₃ ⁻ -N ^d mg kg ⁻¹ | PO ₄ ^{-3e} mg kg ⁻¹ | K ^f mg kg ⁻¹ | Ca ^f mg kg ⁻¹ | Mg ^f mg kg ⁻¹ | Na ^f mg kg ⁻¹ | CEC ^g cmol(+) kg ⁻¹ |
|----------|----------------------------|----------------------------|----------------------------|-----------------|---------------------------------------|---------------------------------------|---------------------------------------------------------------------|-------------------------------------------------------|---------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------------|
| Wyndmere | 753 | 116 | 132 | 6 | 0.19 | 27 | 3.5 | 8.5 | 245 | 1,480 | 343 | 109 | 11.3 |
| Fargo | 119 | 386 | 495 | 8 | 1.64 | 31 | 10 | 6 | 290 | 5,490 | 1,384 | 437 | 40.6 |

EC electrical conductivity, OM organic matter

^a Determined by 1:1 soil/deionized water^b EC determined by 1:1 soil/deionized water^c OM determined by high-temperature combustion^d Determined by 1 M KCl extraction and colorimetric analysis^e Determined using the Olsen method^f Determined from 1 M NH₄-acetate extraction and atomic absorption^g Determined by summation

TDS divided by 640, was 8.5 and 4.8 dS m⁻¹, respectively.

2.2 Experimental Setup

In the greenhouse study, each CGR was applied to each soil at rates of 0%, 8%, and 25% by weight, which equated to an broadcast application rate of about 83 and 260 Mg ha⁻¹ for the 8% and 25% treatments, respectively, so that the final mass of soil plus CGR in each pot was 1.75 kg. All soil–CGR mixtures were mixed by hand in LDPE plastic bags for 5 min to improve homogeneity prior to placement into the pots. Smooth brome (20 seeds) was planted into each treatment. Three replications were used for each treatment. All treatments were initiated and terminated on days of year (DOY) 20 and 99 (2010), respectively. After 21 days, the number of plants in each pot was reduced to 12. All pots were watered with tap water to soil field capacity every other day at the start of the experiment and every day starting on DOY 81. Field capacity was estimated by saturating a sample of each treatment with water, allowing all gravitational water to drain and weighing pots to determine water held. Water soluble plant fertilizer (20–20–20 N–P₂O₅–K₂O; Jack's Classic; JR Peters Inc., Allentown, PA, USA) was mixed at concentrations of 0.5 g L⁻¹ using deionized water (DI), and each pot received 50 mL of this solution on DOY 71 and 95. The bulk fertilizer product also contained 0.2, 0.5, 1.0, 0.5, 0.009, and 0.5 g kg⁻¹ B, Cu, Fe, Mn, Mo, and Zn, respectively. In addition, the bulk product had impurity concentrations of As, Cd, Hg, Pb, and Ni of less than 18, 7.8, 0.04, 47, and 3.7 ng g⁻¹, respectively (Oregon Department of Agriculture 2010).

2.3 Sample Collection and Analysis

At DOY 99, plant shoots were clipped at the soil surface, dried at 25°C using forced air, and mass determined. A 15-cm deep soil sample was also taken from the center of each pot using a stainless steel probe having a diameter of 1.3 cm. Each soil sample was air-dried at 25°C, ground to pass through a 2-mm sieve using a mortar and pestle, and stored in LDPE plastic bags. The soil probe and mortar and pestle were thoroughly cleaned between each sample using deionized (DI) water. Plant roots were separated from the soil remaining in the pot using a root washer, dried at

Table 2 Chemical characterization of the solid phase of concrete grinding residue from two USA roadway grinding locations: Interstate-10 in California (10/CA) and Interstate-94 in Minnesota (94/MN)

| | Chemical parameter | USA roadway identification and location | |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|-----------------------------------------|-------|
| | | 10/CA | 94/MN |
| All extractions and analyses were done using EPA Method 6010B unless otherwise noted. Used with permission, from <i>Journal of Environmental Quality</i> 40:242–247 (2011) <i>BRL</i> below report limit (for Ag, Hg, Pt, Sb, Se, Sn, and Th the BRLs, at respective units noted in the table, were 1.0, 50, 0.2, 1.0, 0.1, 2.0, and 3.6, respectively), <i>NR</i> not reported by the laboratory | Ag (mg kg ⁻¹) | BRL | BRL |
| | Al (g kg ⁻¹) | 12.0 | 9.3 |
| | As (mg kg ⁻¹) | 3.7 | 3.7 |
| | Ba (mg kg ⁻¹) | 70.2 | 219 |
| | Be (mg kg ⁻¹) | 0.4 | 0.6 |
| | Ca (g kg ⁻¹) | 50.1 | 63.3 |
| | Cd (mg kg ⁻¹) | 0.4 | 0.2 |
| | Co (mg kg ⁻¹) | 26.7 | 11.9 |
| | Cr (mg kg ⁻¹) | 16.3 | 17.1 |
| | Hg ^a (ng g ⁻¹) | BRL | BRL |
| | Mg (g kg ⁻¹) | 5.4 | 16.1 |
| | Na (g kg ⁻¹) | 1.5 | NR |
| | Ni (mg kg ⁻¹) | 7.7 | 11.1 |
| | Pb (mg kg ⁻¹) | 15.7 | 2.2 |
| | Pt (mg kg ⁻¹) | BRL | 1.4 |
| | SO ₄ ^{2-b} (mg kg ⁻¹) | 1,240 | 4,130 |
| | Sb (mg kg ⁻¹) | BRL | BRL |
| | Se (mg kg ⁻¹) | BRL | BRL |
| | Sn ^c (mg kg ⁻¹) | 2.2 | BRL |
| | Sr ^c (mg kg ⁻¹) | 136 | 371 |
| | Th (mg kg ⁻¹) | BRL | BRL |
| | V (mg kg ⁻¹) | 27.1 | 24.1 |

^a Determined using EPA Method 7470A

^b Determined using EPA Method 9038

^c Determined using EPA Method 6020A

60°C, and weighed. Soil from each core was analyzed for pH and EC using a 1:1 ratio of soil/DI water and the remaining soil was sent to a private laboratory (Acme Analytical Laboratories Ltd., Vancouver, BC, Canada) for determination of Ag, Al, As, Ba, Be, Ca, Cd, Co, Cr, Hg, Mg, Na, Ni, Pb, Pt, S, Sb, Se, Sn, Sr, Th, and V using aqua regia digestion and inductively coupled plasma–mass spectrometry (ICP-MS) using laboratory protocol (vendor code 1F04). Plant biomass was sent to the same laboratory and analyzed for the above elements using nitric acid–aqua regia digestion and ICP-MS (vendor code 1VE2). The elements N, P, K, B, Cu, Fe, Mn, Mo, and Zn are not reported for the soil or plant chemistry data due to their significant presence in the fertilizer solution whereas discussions of As, Cd, Hg, Ni, and Pb are included in the analysis discussion.

2.4 Statistical Analysis

Data for soils and plants were analyzed using ANOVA (Proc Mixed Ver. 9.1; SAS Institute, Cary,

NC, USA). A three-way ANOVA was conducted with CGR rate, CGR source, and soil type as fixed effects and replication as a random effect. Means of significant tests were separated using paired *t* tests. Plant growth was also compared with soil chemical and physical parameters using a pairwise comparison technique in JMP (Ver. 8.0; SAS Institute, Cary, NC, USA). All analysis was conducted at levels of $\alpha = 0.05$, and significance was accepted at probabilities (*p*) of $p \leq 0.05$ for all statistical tests.

3 Results and Discussion

3.1 Shoot Biomass

Shoot biomass was significantly influenced by the two-way interactions between soil type, CGR source, and CGR rate (Soil×CGR, Soil×Rate, and CGR×Rate; Tables 3, 4). The highest shoot growth was observed in the Wyndmere soil amended with 8%

Table 3 SAS generated *p* values of main effects and interactions for selected physical and chemical parameters of smooth brome grass and soils

| Source | Plant parameters | | | | | Soil parameters | | | | | | | | | |
|---------------|------------------|--------|--------|-------|-------|-----------------|--------|--------|--------|--------|--------|-------|--------|--------|--------|
| | Shoot biomass | Ca | Cd | Cr | Hg | Pb | Sr | pH | EC | Ca | Cd | Cr | Hg | Pb | Sr |
| Soil | <0.001 | 0.212 | <0.001 | 0.009 | 0.842 | 0.016 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0.028 | <0.001 | <0.001 | <0.001 |
| CGR | <0.001 | <0.001 | 0.070 | 0.052 | 0.238 | 0.373 | <0.001 | 0.002 | <0.001 | <0.001 | 0.771 | 0.826 | 0.011 | <0.001 | <0.001 |
| Rate | <0.001 | <0.001 | <0.001 | 0.018 | 0.121 | 0.003 | 0.065 | <0.001 | <0.001 | <0.001 | <0.001 | 0.629 | <0.001 | 0.009 | <0.001 |
| Soil×CGR | 0.005 | 0.237 | 0.706 | 0.892 | 0.428 | 0.255 | 0.684 | 0.830 | 0.865 | 0.007 | 0.253 | 0.826 | 0.483 | 0.012 | 0.014 |
| Soil×Rate | <0.001 | <0.001 | <0.001 | 0.326 | 0.302 | 0.199 | <0.001 | 0.001 | 0.021 | 0.501 | 0.005 | 0.822 | 0.012 | <0.001 | 0.262 |
| CGR×Rate | 0.001 | 0.020 | 0.004 | 0.086 | 0.051 | 0.311 | <0.001 | 0.008 | <0.001 | 0.016 | 0.980 | 0.971 | 0.030 | <0.001 | 0.010 |
| Soil×CGR×Rate | 0.076 | 0.373 | 0.444 | 0.205 | 0.754 | 0.640 | 0.880 | 0.963 | 0.146 | 0.005 | 0.401 | 0.971 | 0.169 | 0.182 | 0.038 |

CGR, regardless of source (Table 4). Both the 0% and 25% rates produced similar shoots in the Wyndmere soil, but the highest CGR application rate reduced shoot biomass in the Fargo soil. Across soil types, the 8% rate generally improved shoot growth, as much as three times greater, compared with the 0% and 25% rates (Table 5). Across CGR application rates, both CGR products resulted in higher shoot production in the Wyndmere soil when compared with the shoots in the Fargo soil (Table 5). Interestingly, shoot growth was not significantly correlated by any of the soil chemical and physical parameters (Pairwise comparison; JMP ver. 8.0, SAS Institute Inc.; data not shown). In many types of soil–plant relation studies, one of the measured soil criterion is exchangeable cations. Here, the concentrations of Ca, Mg, K, and Na were very high and determining exchangeable vs soluble would have been difficult and potentially accepting a type II error. The influence of CGR on smooth brome shoot biomass will likely be variable across application regions, which is complicated by the lack of any one variable measured in this study controlling its health and quality. Root biomasses were the same within respective soils and CGR products and may not be a good indicator of plant health in greenhouse studies.

Of the non-trace elements listed in Table 4 (Ca, Mg, Na, and S), 75% of them were significantly influenced by the two-way interactions of Soil×Rate and CGR×Rate (Table 3; data not shown). Although not all of the trace elements (Table 4) extracted from the plant biomass were significantly influenced by the main effects, Soil and Rate more commonly influenced element concentration than did the type of CGR (70%, 70%, and 30%, respectively; Table 3, data not shown). A select list of non-trace and trace elements and their main effects and interactions are presented in Table 3.

Calcium uptake into the shoots was significantly influenced by CGR, Rate, Soil×Rate, and CGR×Rate (Table 3). In the Wyndmere soil, Ca concentrations were significantly greater ($p \leq 0.05$) in the CGR treatments compared with the control, and in the Fargo soil, concentrations of Ca in the shoots were less effected by CGR additions (Table 4). A similar response in the Fargo soil to CGR was also observed for Mg and S (Table 4). Inherently high soil levels of Ca, Mg, and S in the Fargo soil (Table 1) likely contributed to the decreased concentration differences compared with the

Table 4 Physical and chemical parameters of smooth brome (*B. inermis* Leyss) biomass grown in two different soils (Wyndmere and Fargo) treated with two different concrete grinding residues (94/MN and 10/CA) at three rates of application (0%, 8%, and 25%)

| Chemical/physical parameters | Wyndmere fine sandy loam | | | | | | Fargo silty clay | | | | | |
|------------------------------|--------------------------|--------|-------|------------------------|-------|-------|------------------------|--------|-------|------------------------|-------|-------|
| | 94/MN application rate | | | 10/CA application rate | | | 94/MN application rate | | | 10/CA application rate | | |
| | 0% | 8% | 25% | 0% | 8% | 25% | 0% | 8% | 25% | 0% | 8% | 25% |
| Shoot biomass (g) | 2.84B ^a | 4.51A | 2.04B | 2.84B | 8.23A | 3.46B | 2.97A | 2.66A | 1.4B | 2.97A | 3.65A | 1.21B |
| Root biomass (g) | 3.83A | 6.73A | 6.51A | 3.83A | 3.02A | 5.88A | 3.65A | 3.18A | 4.88A | 3.64A | 7.79A | 4.37A |
| Ba (mg kg ⁻¹) | 19.3A | 17.2A | 14.4A | 19.3A | 19.5A | 13.0B | 13.3A | 12.3AB | 9.70B | 13.3A | 10.5A | 8.83A |
| Ca (g kg ⁻¹) | 3.4B | 6.0A | 5.9A | 3.4B | 4.5A | 4.7A | 4.6B | 4.9AB | 5.8A | 4.6A | 4.4A | 4.8A |
| Cd (mg kg ⁻¹) | 0.12B | 0.22A | 0.24A | 0.12C | 0.26A | 0.16B | 0.12A | 0.12A | 0.15A | 0.12A | 0.12A | 0.09A |
| Co (mg kg ⁻¹) | 0.05A | 0.06A | 0.04A | 0.05B | 0.17A | 0.18A | 0.07A | 0.11A | 0.14A | 0.07B | 0.11B | 0.19A |
| Cr (mg kg ⁻¹) | 0.90A | 0.90A | 0.80A | 0.90A | 0.93A | 1.03A | 0.93A | 1.03A | 1.00A | 0.93B | 0.97B | 1.30A |
| Hg (ng g ⁻¹) | 8.67A | 10.3A | 10.7A | 8.67A | 11.3A | 9.00A | 10.0A | 10.3A | 11.0A | 10.0A | 10.7A | 7.33B |
| Mg (g kg ⁻¹) | 2.7A | 2.3A | 1.7B | 2.7A | 2.0B | 1.9B | 3.6A | 2.9AB | 2.6B | 3.6A | 3.1B | 2.0 C |
| Na (g kg ⁻¹) | 0.02B | 0.4B | 1.6A | 0.02A | 0.09A | 0.2A | 0.1B | 0.1B | 0.4A | 0.1A | 0.1A | 0.1A |
| Ni (mg kg ⁻¹) | 0.43B | 0.70AB | 1.03A | 0.43B | 0.87A | 0.80A | 0.73B | 0.83AB | 0.97A | 0.73A | 1.00A | 1.33A |
| Pb (mg kg ⁻¹) | 0.97A | 0.71A | 0.82A | 0.97A | 0.79A | 0.49A | 2.10A | 1.07B | 0.79B | 2.10A | 1.64A | 2.21A |
| S (g kg ⁻¹) | 1.3B | 1.9B | 2.9A | 1.3B | 2.9A | 3.5A | 3.0A | 2.2B | 3.2A | 3.0B | 2.7B | 3.5A |
| Se (mg kg ⁻¹) | 0.20A | 0.53A | 1.73A | 0.20C | 3.13B | 7.03A | 0.27B | 0.47A | 0.60A | 0.27C | 4.97B | 6.33A |
| Sn (mg kg ⁻¹) | 0.03A | 0.03A | 0.02A | 0.03B | 0.05A | 0.02B | 0.05A | 0.03A | 0.03A | 0.05A | 0.05A | 0.04A |
| Sr (mg kg ⁻¹) | 11.0B | 18.0A | 20.2A | 10.6A | 11.0A | 11.5A | 29.0A | 24.6A | 24.7A | 29.0A | 19.8B | 15.3B |

Concentrations of Ag, Al, As, Be, Pt, Sb, Th, and V were below the quantification limit reported by the laboratory and are not reported

^a Means followed by different uppercase letters within rows under respective concrete grinding residue source (i.e., 94/MN application rate or 10/CA application rate) and soil (Wyndmere fine sandy loam or Fargo silty clay) are significantly different at $p \leq 0.05$

Table 5 Dry shoot biomass two-way interactions observed in the greenhouse pot study. (A) Soil×Rate, (B) CGR source×Rate, and (C) Soil×CGR source

| Rate | Soil (g dry biomass) | |
|-------|----------------------|---------|
| | Wyndmere | Fargo |
| 0% | 2.84 B ^a | 2.97 B |
| 8% | 6.37 A | 3.15 B |
| 25% | 2.75 B | 1.31 C |
| Rate | CGR (g dry biomass) | |
| | 94/MN | 10/CA |
| 0% | 2.90 BC | 2.90 BC |
| 8% | 3.58 B | 5.94 A |
| 25% | 1.72 D | 2.34 CD |
| CGR | Soil (g dry biomass) | |
| | Wyndmere | Fargo |
| 94/MN | 3.13 B | 2.34 C |
| 10/CA | 4.84 A | 2.61 BC |

^a Means for each two-way interaction followed by the same uppercase letter within each group are not significantly different at $p \leq 0.05$

Wyndmere soil. Decreased Mg shoot uptake in the 25% CGR treatments may have been due to Ca being preferentially translocated into the plants. A study regarding Mg uptake in CGR amended soils would need to be conducted to determine if reduced Mg in the shoots negatively impacts plant health at the levels reported here.

Soil type and CGR rate significantly altered shoot Cr, Pb, and Sr levels (Table 3). When grown in Fargo soil, the shoot Cr, Pb, and Sr concentrations were elevated compared with shoots grown in the Wyndmere soil, and additions of CGR did not consistently impact shoot quality compared with the control (0%; Table 4). Concrete grinding residue rate also affected Cr and Pb levels observed in shoots (Tables 3 and 4). The maximum levels of Cr and Pb in shoot biomass reported here (Table 4; 1.30 and 2.21 mg kg⁻¹, respectively) are lower than concentrations reported in plant uptake studies conducted by Xu and Jaffe (2006) (2.71 mg kg⁻¹; *Typha latifolia*), Pierzynski and Schwab (1993) (2.6 mg kg⁻¹; *Glycine max*), respectively, but

greater here for Sr (29.0 mg kg^{-1}) than the Collins and Burch (1970) study (5.1 mg kg^{-1} ; *Brassica alba*). Uptake of Sr has been shown to be positively correlated with Ca concentrations in the soil (Veresoglou et al. 1995). Given the wide range of plant species found in roadside soils (Forman and Alexander 1998; Tikka et al. 2001), impacts of trace elements from CGR will likely be highly variable.

Of the 40 individual shoot-trace element comparisons in Table 4, 68% of the trace metals had the same concentration or lower in the high rate (25%) compared with the control treatments (0%). Trace metal concentrations in the shoots were variable, and only Ni showed enhanced uptake in both the 94/MN and 10/CA-Fargo soil treatments. These results may not be reproducible in the field due to the presence of other trace elements in roadside soils (Ho and Tai 1988; Gratani et al. 1992; Garcia and Millan 1998; Shanmugam 2004), which would greatly complicate identifying the source of these elements within shoot biomass. Furthermore, when CGR is added to the soil, changes in soil pH, ionic strength, presence and concentration of anions and cations, plant species present in roadside soils, presence/type of oxides in the soil, presence/concentration of organic matter in the soil, competition for root uptake, and competition for exchange sites with other cations will all influence accumulation of trace metals in plant biomass (Collander 1941; Menzel 1954; Naidu et al. 1994; Roca and Vallejo 1995; Singh and Myhr 1998; Norvell et al. 2000; Basta et al. 2005; Abe et al. 2008).

3.2 Soil Chemistry

Soil pH and EC were significantly influenced by the two-way interactions, Soil \times Rate and CGR \times Rate (Table 3). Soil pH was significantly greater ($p\leq 0.05$) for both soils when CGR was applied, regardless of rate (Table 6). The CGR liming effects were similar to the results of Shanmugam (2004), where they report that at one test site CGR-treated and untreated areas had soil pH values ranging from about 7.0 to about 8.5, respectively. Increases in soil pH may negatively impact availability of some micronutrients to roadside soils (McKenzie 2003). Application of 25% by weight CGR significantly increased EC of both soils compared with the control and the low, 8% rate (Table 6). The 94/MN-treated soils exhibited a greater increase in EC compared with the soils treated with

10/CA at respective application rates (Table 6), which was not unexpected due to the 94/MN having nearly double the solution phase EC compared with the 10/CA (DeSutter et al. 2011).

All of the non-trace elements, described here as Ca, Mg, Na, S, and Al, were significantly influenced by the main effects Soil and CGR, and the two-way interaction CGR \times Rate, which indicates that the soil type and source of CGR are very important for controlling the concentration of these elements in the soil. Calcium and Na concentrations in the CGR-treated soils were significantly greater ($p\leq 0.05$) in the 25% treatments compared with the 8% and controls (Table 6). Calcium is the major cation used in Portland cement production and is added as tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite (US Department of Transportation 2010), and calcium sulfate (Bye 1983) and is an essential plant nutrient that is applied through CGR application. The concentration of sodium oxide in Portland cement can vary from 1 to 10 g kg^{-1} (Bye 1983). Although exchangeable Na was not determined here, addition of any appreciable amount of Na to soils could lead to dispersion if the soil solution EC is low, based upon electric double-layer theory (Essington 2004). However, given the increase in total Ca and EC to the soil through the addition of CGR, the potential for soil dispersion seems remote.

Aluminum was significantly greater ($p\leq 0.05$) in the Wyndmere soil with the high CGR rate (25%) treatments compared with the low CGR rate (8%) and controls (0%), but not significantly different across treatments in the Fargo soil (Table 6). Magnesium concentrations varied across soils and CGR products and were significantly greater ($p\leq 0.05$) in the 25% compared with the 8% and control soils for the Wyndmere soil (Table 6). Sulfur was typically greater ($p\leq 0.05$) in the 25% treatments compared with the 8% and controls (Table 6), which may have been due to calcium sulfate being added during the cement production process as noted above. Increases in exchangeable Al or elemental S may lead to lower soil pH values, but this would likely be nullified by the liming effect of the CGR.

Considering all 16 trace elements from Table 6, 100%, 50%, and 75% of them were significantly influenced by Soil, CGR, and Rate, respectively, which indicated that these main effects are all important when considering environmental impacts

Table 6 Soil chemical parameters resulting from the application of two concrete grinding residues (94/MN and 10/CA) at three rates of application (0%, 8%, and 25%) to two soils (Wyndmere and Fargo)

| Chemical parameter | Wyndmere fine sandy loam | | | | | | Fargo silty clay | | | | | |
|---------------------------|--------------------------|--------|-------|------------------------|--------|-------|------------------------|--------|--------|------------------------|--------|-------|
| | 94/MN application rate | | | 10/CA application rate | | | 94/MN application rate | | | 10/CA application rate | | |
| | 0% | 8% | 25% | 0% | 8% | 25% | 0% | 8% | 25% | 0% | 8% | 25% |
| pH | 8.0B ^a | 8.5A | 8.6A | 8.0B | 8.6A | 8.9A | 7.9B | 8.1A | 8.2A | 7.9C | 8.3B | 8.5A |
| EC (dS m ⁻¹) | 0.21C | 0.92B | 2.26A | 0.21B | 0.32B | 0.82A | 1.37C | 1.85B | 3.09A | 1.37B | 1.04C | 1.90A |
| Ag (mg kg ⁻¹) | 0.05A | 0.05A | 0.04A | 0.05B | 0.05B | 0.06A | 0.11A | 0.10B | 0.09C | 0.11A | 0.10A | 0.11A |
| Al (g kg ⁻¹) | 6.4B | 6.5B | 7.2A | 6.4C | 7.0B | 9.1A | 17.1A | 16.5A | 16.4A | 17.1A | 16.4A | 17.3A |
| As (mg kg ⁻¹) | 2.87A | 2.97A | 3.00A | 2.87B | 3.07AB | 3.30A | 8.10A | 7.47B | 6.87C | 8.10A | 7.83A | 7.13B |
| Ba (mg kg ⁻¹) | 116C | 126B | 142A | 116A | 117A | 114A | 191A | 178B | 190A | 191A | 177A | 161B |
| Be (mg kg ⁻¹) | 0.37A | 0.40A | 0.40A | 0.37A | 0.33A | 0.30A | 0.70A | 0.80A | 0.70A | 0.70A | 0.83A | 0.73A |
| Ca (g kg ⁻¹) | 4.2C | 13.3B | 32.8A | 4.2C | 10.1B | 24.8A | 37.6C | 45.2B | 62.3A | 37.6B | 42.8B | 62.5A |
| Cd (mg kg ⁻¹) | 0.40A | 0.38A | 0.36A | 0.40A | 0.39A | 0.40A | 0.66A | 0.55A | 0.60A | 0.66A | 0.60AB | 0.52B |
| Co (mg kg ⁻¹) | 5.70B | 6.07B | 6.77A | 5.70B | 7.47B | 13.7A | 11.4A | 11.3A | 11.6A | 11.4B | 13.5B | 22.5A |
| Cr (mg kg ⁻¹) | 29.7A | 26.9A | 25.7A | 29.7A | 22.1A | 26.1A | 35.9A | 34.3A | 32.7A | 35.9A | 34.3A | 32.7A |
| Hg (ng g ⁻¹) | 26.3A | 15.7B | 14.3B | 26.3A | 11.3B | 9.00B | 35.0A | 32.3AB | 26.7B | 35.0A | 31.7A | 15.0B |
| Mg (g kg ⁻¹) | 2.6C | 3.7B | 5.3A | 2.6B | 2.8B | 3.6A | 16.0A | 16.1A | 16.3A | 16.0A | 14.8A | 11.7B |
| Na (g kg ⁻¹) | 0.2C | 0.6B | 1.5A | 0.2B | 0.2B | 0.5A | 0.5C | 0.9B | 1.8A | 0.5B | 0.5B | 1.0A |
| Ni (mg kg ⁻¹) | 16.2A | 15.2A | 14.4A | 16.2A | 15.4AB | 15.0B | 34.4A | 31.6AB | 28.2B | 34.4A | 31.1A | 23.4B |
| Pb (mg kg ⁻¹) | 7.17A | 6.47B | 6.13B | 7.17C | 8.15B | 11.9A | 20.3A | 17.0B | 15.0B | 20.3A | 20.5A | 23.1A |
| S (g kg ⁻¹) | 0.1C | 0.3B | 0.6A | 0.1C | 0.2B | 0.7A | 0.8AB | 0.6B | 0.9A | 0.8B | 0.6B | 1.6A |
| Sb (mg kg ⁻¹) | 0.19B | 0.20B | 0.21A | 0.19A | 0.19A | 0.19A | 0.51A | 0.35B | 0.35B | 0.51A | 0.42A | 0.32B |
| Se (mg kg ⁻¹) | 0.33A | 0.37A | 0.43A | 0.33A | 0.37A | 0.37A | 0.85A | 0.60B | 0.63AB | 0.85A | 0.70AB | 0.47B |
| Sn (mg kg ⁻¹) | 0.30B | 0.30B | 0.37A | 0.30C | 0.37B | 0.50A | 0.90A | 0.73B | 0.73B | 0.90A | 0.87A | 1.00A |
| Sr (mg kg ⁻¹) | 23.6C | 40.4B | 72.8A | 23.6C | 31.1B | 50.8A | 79.7B | 87.9B | 116A | 79.7B | 83.4B | 113A |
| Th (mg kg ⁻¹) | 2.93B | 3.03AB | 2.31A | 2.93B | 3.10B | 3.63A | 6.40A | 5.80AB | 5.63B | 6.40A | 6.13AB | 5.43B |
| V (mg kg ⁻¹) | 22.7A | 22.7A | 22.7A | 22.7B | 23.7B | 26.0A | 64.5A | 59.3AB | 56.0B | 64.5A | 60.0AB | 52.3B |

Concentrations of Pt were below the quantification limit reported by the laboratory and are not reported

^a Means followed by different uppercase letters within rows under respective concrete grinding residue source (i.e., 94/MN application rate or 10/CA application rate) and soil (Wyndmere fine sandy loam or Fargo silty clay) are significantly different at $p \leq 0.05$

of CGR to soils. The two-way interactions did not influence trace element concentration as consistently as the main effects, but Soil×Rate and CGR×Rate did significantly influence 75% and 47% of these element concentrations, respectively (Table 3). Only 31% of the trace elements were significantly influenced by the three-way interaction. A select list of non-trace and trace elements and their main effects and interactions are presented in Table 3.

Addition of CGR to soil resulted in many of the trace elements being diluted or having the same concentrations as the control treatments. For example, Cd was not significantly different ($p>0.05$) within respective Wyndmere treatments and was significantly diluted ($p\leq 0.05$) for the 10/CA-treated Fargo soil (Table 6). Other trace elements that showed similar results as Cd were Be, Cr, Hg, Ni, and Se. The only trace element that was significantly greater ($p\leq 0.05$) in the high CGR rate (25%), when compared with the control treatments (0%), was Sr, which had a maximum concentration of 116 mg kg^{-1} in the 94/MN–Fargo soil treatment. Many of the other trace elements were variably diluted or concentrated within the treatments and Pt was below the quantification limit reported by the laboratory. Concentrations of the trace metals reported here were all within the range reported for non-contaminated soils (McBride 1994; Essington 2004).

Addition of 25% CGR significantly decreased ($p\leq 0.05$) Hg concentrations in both soils compared with the levels in the controls (Table 6). The two CGR sources used in this study had Hg concentrations below 50 ng g^{-1} , which was then further diluted by preparing the CGR treatments. Mercury concentrations in CGR may not always be as low as those used in this study (DeSutter et al. 2011). The Hg results reported here are similar to those reported in DeSutter et al. (2010) for roadside soils in North Dakota.

4 Conclusion

The objective of this research was to determine how CGR additions to soil impact growth of smooth brome and soil properties. Concrete grinding residues will vary in their physical and chemical nature, and their impact on the environment will depend on the concrete composition, quality of grinding water, and the presence of organics on road surfaces. Several

conclusions can be drawn from the research conducted here, including (1) soil pH and EC will likely increase after CGR application due to the liming potential and total dissolved salts present in CGR, respectively; (2) smooth brome growth will be a function of soil type, CGR, and rate of application of this by-product, and thus, CGR additions to soil will variably impact this plant species; (3) uptake of Ca, an essential plant nutrient, by smooth brome will likely be accentuated by the application of CGR; (4) trace metal uptake by smooth brome is variable and will depend on CGR and many soil chemical properties; (5) soil application rates of CGR will likely not increase trace metal levels in either soils or smooth brome above those found in uncontaminated soils; and (6) application of CGR at the 8% rate (83 Mg ha^{-1} ; 37 t ac^{-1}) was generally beneficial for smooth brome growth, but application rates greater than 8% should be well justified and are not recommended since the rate at which smooth brome responded negatively was not determined here.

Even though this by-product has been widely produced across the USA since the 1960s, very little research has been conducted on its impacts on the environment. As a waste by-product, CGR bears little resemblance to biosolids, coal combustion waste ash, or foundry sands. Thus, regulation of CGR application to soils will need to be based on results such as those presented here and the other papers referenced within. Although the total dissolved solids concentration would be difficult for grinding companies to control, limiting the liming potential of CGR should be strongly considered as a best management practice.

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