

Article

Creeping Bentgrass Fairway Wear Resistance by Granular Topdressing of Ca/Mg-rich Liming Agents

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Abstract: Depletion of extractable silicon (Si) from surface soil depths has been observed in managed production systems. While not characterized as a plant essential nutrient, Si accrues in epidermal and vascular tissue of monocotyledonous plants. A field evaluation of granular Ca/Mg-rich liming agents was initiated on a creeping bentgrass (*Agrostis stolonifera* L. cv. Declaration) fairway in 2010. Excluding the control, treatments comprised 2440 kg (ha year)⁻¹ topdressing of calcitic/dolomitic blended limestone or Ca/Mg-SiO₃ in semi-annual or more frequent “split” applications. Each week of the 2011 and 2012 growing seasons, a dedicated wear simulator trafficked the fairway plots. Measures of canopy quality, clipping yield, tissue composition, soil pH, and plant-available soil Si levels were collected frequently. The described Ca/Mg-SiO₃ annual topdressing rates correlated with acetic acid extractable Si levels >30 mg kg⁻¹ in the 0- to 5-cm soil depth. Neither creeping bentgrass vigor, nutrition, nor leaf water content was influenced by significantly elevated levels of soil and tissue Si. Relative to non-trafficked plots, all split plots within trafficked main plots showed similarly reduced canopy quality regardless of topdressing treatment. If a critical threshold leaf Si concentration for creeping bentgrass wear tolerance enhancement exists, it is unlikely <11 g Si kg⁻¹.

Keywords: abiotic stress; silicates; silicon offtake; traffic; turfgrass

1. Introduction

Silicon (Si) is the second-most abundant element in earth’s crust and a steadfast component of soil minerals [1]. Though not characterized as an essential nutrient, Si accumulates in the plant biomass of numerous genera [2]. Monocotyledonous plant uptake results in apoplastic silica deposition in the epidermal and cuticular tissue of shoots and the exodermal and endodermal tissue of roots [3–6].

Silicon depletion from shallow depths of production systems has been readily linked to plant assimilation [7,8]. Accumulation of Si in rice stalks has been correlated with application rate of soluble, silicate-rich amendments [9,10]. Topdressing or incorporating Ca- and/or Mg-SiO₃ conditioner(s) into rootzones underlying creeping bentgrass (*Agrostis stolonifera* L.), tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.), perennial ryegrass (*Lolium perenne* L.), bermudagrass (*Cynodon dactylon* L.), and zoysiagrass (*Zoysia japonica* Steud.) have resulted in statistically significant increases in Si accumulation within leaf tissue [11–15]; whereas, Si fertilizer applications to seashore paspalum (*Paspalum vaginatum* L.) resulted in significant increases of leaf Si during one of two field evaluations [16]. Similarly, spray application of liquid Si fertilizers to creeping bentgrass resulted in significant leaf concentration increase in one of the two recent field studies conducted in the Southern United States [17,18].

Calcium silicate is a dense, granular by-product of the steel industry that has become less ubiquitous with time in the United States. With a calcium carbonate equivalency ranging from 50 to

85%, calcium silicate has long served as an eligible, regionally cost-effective ingredient of cement and agricultural limestone products [19,20]. While neutralization of exchangeable acidity by traditional carbonate and hydr/oxide agents generate CO_2 and/or H_2O [20], the same by Ca/MgSiO_3 produces silicic acid, H_4SiO_4 [13]. This silicate form is sparingly soluble, but dependably absorbed by roots and distributed to cuticular, vascular, and epidermal tissues [3,4,21].

For superintendents of intensely-used golf courses worldwide, wear injury is an abiotic stress of concern. While direct effects include tearing, abrasion, and compression on leaf/shoot tissue, indirect effects of wear injury to turfgrass include reduced utility, pest resistance, and visual appeal [22,23]. Silicic acid deposition in vegetative tissues more likely imparts structural resilience and pathogen resistance by apoplastic obstruction than defense mechanism stimulation [2,24]. Rice stalk cell wall silicification, occurring at a notably lesser metabolic cost than lignification, has subsequently demonstrated equal resistance to applied compressive force [25–27].

Creeping bentgrass is a cool-season turfgrass species recognized for its recuperation potential, low mowing height tolerance, and resilience under sub- and supra-optimal temperatures [23]. Where cool-season turfgrasses are well-adapted and hardy perennial fairway cover is desired, the light green color of creeping bentgrass contrasts sharply against darker-green species maintained as surrounding roughs. Given its Si accumulator classification and widespread use under highly-trafficked conditions [28], creeping bentgrass comprises an ideal candidate for field evaluation. Therefore, the objectives of this field research are to comprehensively assess (i) soil and leaf tissue response of a creeping bentgrass fairway to Ca/Mg-rich liming agent type and topdressing frequency, and (ii) canopy color and density response to wear/traffic treatment, the described liming agent treatments, and their interaction.

2. Materials and Methods

The methods described here are highly similar to those used in a previously published study [13], but are detailed again to support comprehensive interpretation of the present experiment. A two-year field trial evaluating commercial granular liming agents commenced November 2010 on a one-year old creeping bentgrass (*Agrostis stolonifera* L. cv. Declaration) fairway maintained at the Joseph Valentine Turfgrass Research Center (University Park, PA). The Hagerstown silt loam (fine, mixed, mesic, typic hapludalfs) comprising the fairway rootzone was appraised to a 15-cm depth in September 2010. Three (3) composite samples were submitted to the Pennsylvania State Univ. Agricultural Analytical Services Laboratory (PSU-AASL) for basic fertility assessment [20]. The experiment was arranged as a split-plot in a randomized complete block design of five (5) replicates. One of the two main plots (8.2 × 3.0 m) in each replicate block was randomly assigned systematic wear treatment. Weekly wear simulator passes were applied in June through September in 2011 and June through late August in 2012. While two passes of the pull-behind wear simulator introduce the mean number of cleat dimples incurred between the mid-field hash marks of a regulation US football field during a 60-minute game [29], this study employed three successive passes over the wear main plots on a single day each week (Figure 1).

Three of the four “sub-plots” (1.8 × 3.0 m, 0.3 m borders) in each main plot were topdressed by pelletized liming agents at a 2440 kg (ha year)⁻¹ rate, while the fourth was left untreated as an experimental control. Granular applications were initiated in November 2010, followed by either irrigation or a rainfall event. Liming agent treatments comprised a 1:1 blend of pelletized dolomitic and calcitic limestone, Ca/MgCO₃ (OldCastle Lawn & Garden, Thomasville, PA, USA), or granular Ca/Mg-silicate (SiO₃) “CrossOver” (Harsco Minerals Intl., Sarver, PA, USA) delivered by equal semi-annual topdressings in Fall and Spring (Table 1). The final liming agent treatment was similar to the last in that 1220 kg Ca/Mg-silicate was applied per hectare each Fall, with the remaining 1220 kg granular Ca/Mg-silicate applied over four or five monthly “split-topdressings” initiated in April 2011 or March 2012 respectively. Mowing (thrice weekly at a 1.2 cm height of cut) was delayed for 5 d following in-season granular applications.



Figure 1. Pull-behind wear simulator applying wear treatment to creeping bentgrass fairway main plots, August 2011.

Table 1. Guaranteed analysis of granular liming agents (per manufacturers' labels).

Liming Agent	Ca	Cu	Fe	Mg	Mn	Si	CaCO ₃ Equiv.
	g kg ⁻¹						
Harsco Minerals Ca/MgSiO ₃	240	5	18	60	5	250	790
OldCastle pelletized Ca/MgCO ₃	265	-	-	60	-	-	940

Preliminary sample results revealed slightly-acidic pH and suitable saturation of an 8.3 meq (100 g soil)⁻¹ cation exchange capacity. Likewise, Mehlich-3 extractable soil P (101 mg kg⁻¹) resided within the optimal range for a mature creeping bentgrass fairway system. Thus, supplemental fertilization practices were limited to monthly applications of various urea fertilizers to ensure plant-availability of 14 to 29 kg N ha⁻¹ per growing month each year of the study [30–32].

Triplicate soil samples at the 0- to 15-cm depth were collected from all non-trafficked sub-plots in mid- and late-summer 2011, and in spring 2012. Soil cores were divided into 0 to 5, 5 to 10, and 10 to 15 cm depth segments, dried in a forced-air oven (70 °C) for 72 h, and ground to pass a 1-mm sieve. These depth segments were sieved prior to splitting for 1:1 soil pH measures or 0.5 M acetic acid soil extraction of plant-available Si [9,13,33].

Clipping yields were collected over a single, lengthwise pass across non-worn sub-plots in June, July, and September 2011; and June and August 2012. The primary justification for which was protecting shoot tissue from contamination by silica-rich soil particles during weekly mechanized traffic simulator transits. Leaf clippings were collected in a labelled paper bag and dried to constant mass in a forced-air

oven (70 °C). However, field collection in July 2011 and June 2012 included immediate diversion of an approximately 1 g fresh clipping sub-sample into a previously labelled and weighed, 60-mL sample bag. These sealed sample bags were re-weighed to 0.1 mg resolution within 4 h of collection, then opened and dried in a forced-air oven (70 °C). Once its contents were thoroughly dry, each bag was re-weighed, then recombined with its original paper bag contents before weighing to 0.1-mg resolution. These dried clipping yields were split for Si-extraction [34] or acid digestion for plant essential nutrient concentration analysis by PSU-AASL [13].

Every 10 ± 5 days from late June through September 2011 or August 2012, quadruplicate measures of canopy reflectance facilitated calculation of the normalized differential vegetative index (NDVI) and the dark green color index (DGCI) as highly repeatable and resolute canopy density and canopy color proxies, respectively [13,30,32,35].

Soil pH and plant-available soil Si levels were sorted by depth before modeled by treatment using PROC MIXED (SAS Institute, v. 8.2, Cary, NC, USA). Main effect of liming agent on soil pH, soil Si, clipping yield, leaf H₂O content, leaf Si content, Si offtake, or tissue nutrient concentration was F-tested by its block interaction term (df = 12). Repeated measures were analyzed as split-plots in time from initiation. Time-series covariate structures, selected using best fit criteria, facilitated F-tests of time and time interaction by the residual error term (df = 16, 32, or 63 for leaf H₂O, soil pH and Si, or all other dependent variables, respectively).

The effect of wear (main plot) treatment on canopy density or canopy color was F-tested using its block interaction term (df = 4). The remaining liming agent source and its interaction with wear were F-tested using the block×wear×liming agent source (df = 24). Repeated canopy quality indices were treated as split-split-plots in time from initiation. Fit-selected covariate structures facilitated F-tests of time and time interactions by the residual error term (df = 765).

Model diagnostics identified outliers ($\leq 1\%$ of observations) for satisfaction of constant variance, error independence, and normal distribution of error ANOVA assumptions. All main and sub-plot effect hypothesis tests employed two-tailed separation of treatment means by Fisher's protected least significant difference (LSD) at the 0.05 alpha level. Stepwise regression of leaf Si by cumulative topdressing level and months elapsed since was facilitated by PROC REG (SAS Institute, v. 8.2, Cary, NC, USA).

3. Results

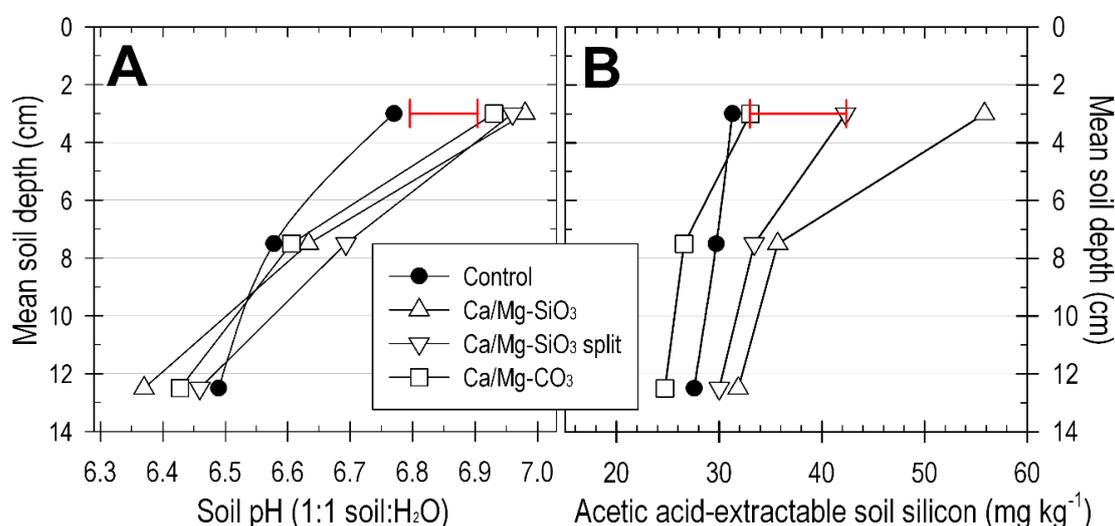
3.1. Soil pH and Silicon Availability

Liming agent treatment was a significant source of variation in soil pH or extractable Si only in the 0 to 5 cm depth (Table 2). Pooled main effects of these influential soil measures are presented by sampling depth (Figure 2). Each liming agent treatment significantly increased pH in the 0 to 5 cm soil depth relative to the untreated control plots (Figure 2A). No significant differences in experiment-wide mean soil pH were observed between the three liming agent treatments, despite the greater acid neutralizing power of the calcitic/dolomitic limestone treatment. Soil pH levels decreased with sample depth regardless of topdressing treatment (Figure 2A).

Likewise, in the 0- to 5-cm soil sampling depth, only the silicate-rich liming agents increased extractable Si levels relative to the untreated control plots (Figure 2B). At this uppermost soil depth, plots receiving Ca/Mg-SiO₃ as semi-annual topdressings showed significantly higher concentrations of extractable Si than plots receiving lighter, more frequent "split" topdressings of the same liming agent. Levels of extractable Si decreased with soil depth regardless of the topdressing treatment (Figure 2B).

Table 2. ANOVA of creeping bentgrass fairway soil pH (1:1) and 0.5 M acetic acid extractable silicon level, by soil depth and source.

Source	df	0 to 5 cm	5 to 10 cm	10 to 15 cm
		Soil pH	P (F-ratio < F-crit)	
Liming agent treatment (LAT)	3	0.004	0.139	0.072
Month after initiation (MAI)	2	0.066	0.046	0.003
LAT × MAI	6	0.207	0.044	0.612
		Extractable Si		P (F-ratio < F-crit)
LAT	3	<0.001	0.195	0.427
MAI	2	<0.001	<0.001	<0.001
LAT × MAI	6	0.040	0.359	0.930

**Figure 2.** (A) Creeping bentgrass fairway mean soil pH (1:1) by liming agent treatment and sample depth. (B) Mean acetic-acid (0.5 M) extractable soil silicon by liming agent and sample depth. For soil chemical property at depth(s) indicated, error bars show least significant difference ($\alpha = 0.05$) between treatment means.

Liming agent treatment and sample date interacted to influence extractable soil silicon level in the uppermost soil depth segment (Table 2). Soil Si levels by liming agent treatment, sample depth, and month after initiation (MAI) are described in Figure 3. On the first soil sampling, eight months after initiation (MAI), the 2440 kg ha⁻¹ annual treatment applications had all been topdressed. Extractable Si level in the 0- to 5-cm soil depth segment of plots receiving the semi-annual Ca/Mg-silicate topdressings exceeded levels observed in untreated or limestone-treated plots (Figure 3A). In the 0 to 5 cm sampling depth, soil Si levels decreased significantly between 8 and 10 MAI, while Ca/Mg-SiO₃-treated plots showed significantly greater Si levels than limestone-treated plots 10 MAI. Silicate liming agent topdressed at the heavier, less frequent rate supported statistically greater soil Si levels than all other plots in the 0 to 5 cm sampling depth 15 MAI, when soil Si increased to maximum observed concentrations (Figure 3A). While similar trends were observed over time in the 5 to 10 or 10 to 15 cm soil depth segments, extractable Si levels diminished with depth and no significant differences between treatments were observed (Figure 3B,C).

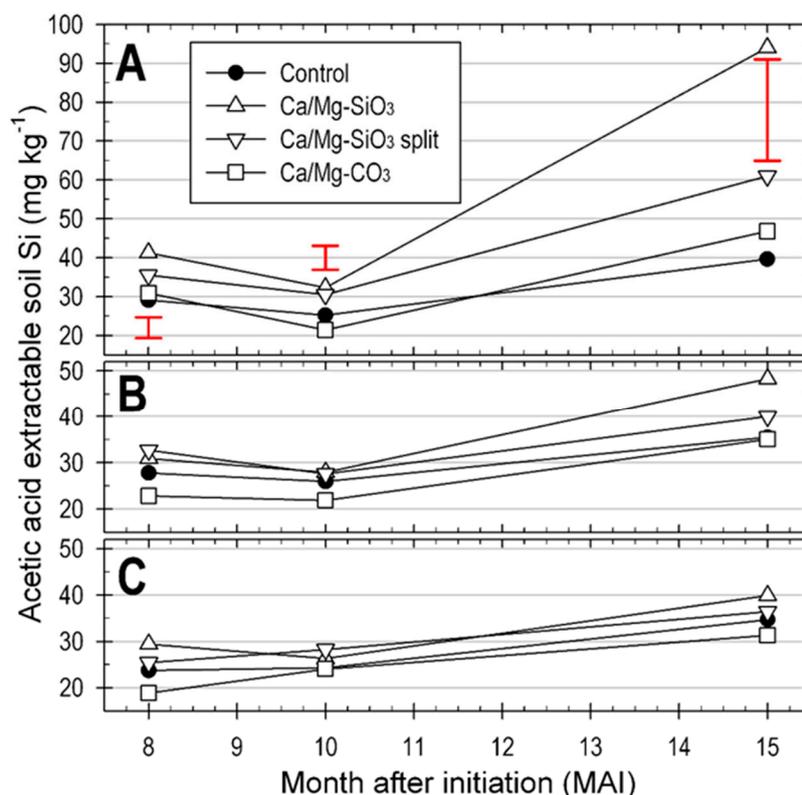


Figure 3. Acetic-acid (0.5 M) extractable soil Si within (A) 0 to 5 cm, (B) 5 to 10 cm, or (C) 10 to 15 cm creeping bentgrass rootzone depth by liming agent and month after initiation (MAI). For soil depth and MAI specified, error bars depict least significant difference (alpha = 0.05) between treatments.

3.2. Turfgrass Vigor, Si Assimilation, Leaf H₂O Status, and Nutrition

Neither treatment nor the interaction of treatment and time statistically influenced the mean daily clipping yield pooled across the three sample events in 2011 and two events in 2012 (Table 3). Varying between 4.5 and 10.5 g Si kg⁻¹ across data collections, mean leaf Si content of plots receiving Ca/Mg-SiO₃ topdressing statistically exceeded the levels observed of sub-plots not receiving SiO₃ liming agents (Table 3). Likewise, liming agent treatment influenced mean Si offtake, where levels from plots treated by Ca/Mg-SiO₃ were significantly greater than that from control or limed subplots (Table 3).

Table 3. ANOVA of creeping bentgrass fairway shoot growth/vigor, leaf Si accumulation, and leaf H₂O status with separation of experiment-wide means where main effects were significant.

Source	df	Clipping Yield	Leaf Si	Si Offtake	df	Leaf H ₂ O
<i>P</i> (F-ratio < F-crit)						
Liming agent treatment (LAT)	3	0.364	<0.001	0.001	3	0.934
Month after initiation (MAI)	4	<0.001	<0.001	<0.001	1	<0.001
LAT × MAI	12	0.636	0.006	0.411	3	0.369
LAT, 2440 kg (ha year)⁻¹		kg ha⁻¹	g kg⁻¹	g ha⁻¹		g kg⁻¹
Control		9.88	5.64	57.78		751.8
Ca/Mg-SiO ₃		10.76	7.65	83.74		751.4
Ca/Mg-SiO ₃ SPL		9.58	7.84	75.74		748.7
Ca/Mg-CO ₃		9.97	6.00	59.63		750.0
Least significant difference, alpha = 0.05		-	0.52	12.33		-

Silicon offtake by liming agent treatment did not depend on the sample date, but topdressing treatments did significantly interact with MAI to affect the leaf Si levels (Table 3). In plots receiving the split Ca/Mg-silicate treatment, leaf Si levels significantly exceeded those observed in lime- or un-treated plots 8 to 21 MAI (Figure 4). Plots treated semi-annually by 2440 kg Ca/Mg-SiO₃ (ha year)⁻¹ demonstrated elevated Si content in clippings collected 7, 8, 19, and 21 MAI, but statistically equivalent leaf Si relative to limestone-treated plots 10 MAI (Figure 4).

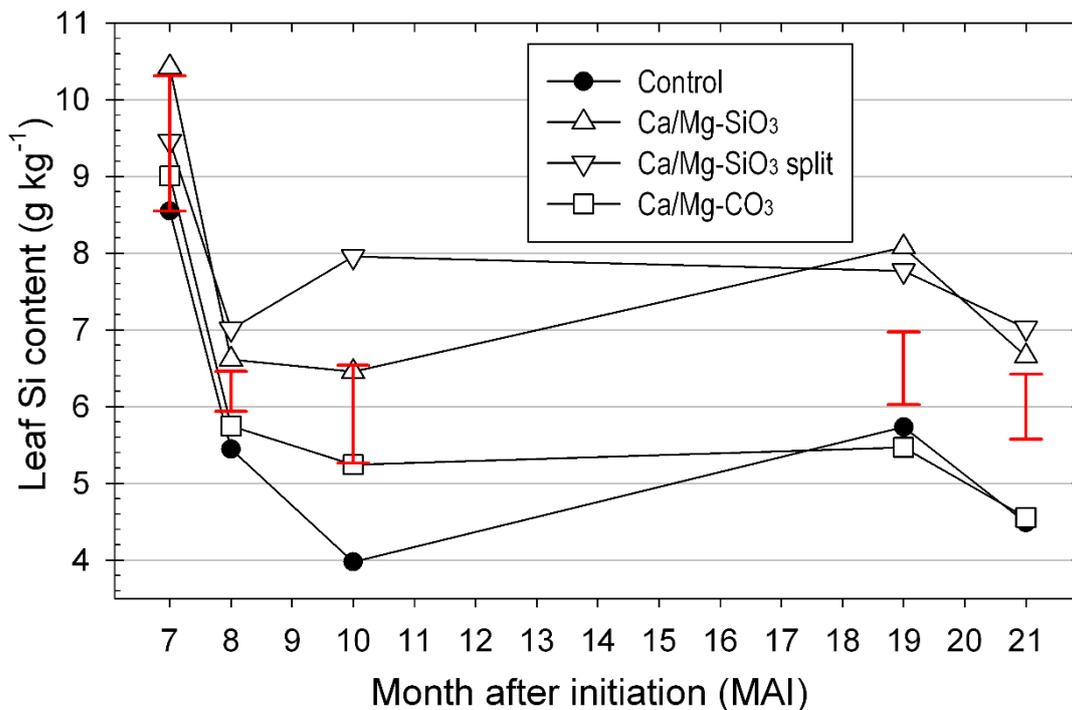


Figure 4. Leaf silicon concentration by liming agent treatment and month after initiation (MAI). For MAI specified, error bars depict least significant difference (alpha = 0.05) between treatments.

Creeping bentgrass clipping leaf water content was significantly influenced by the observation date only. Mean leaf water content in July 2011 was observed between a 725 and 735 g kg⁻¹ range among the liming agent treatments, while leaf water contents of 770 to 774 g kg⁻¹ were measured in June 2012. While plant essential nutrient concentrations were measured and observed to be statistically influenced by observation date and/or liming agent treatment, all leaf tissue nutrient concentrations (data not shown) fell at the upper end of recommended ranges [36].

3.3. Turfgrass Traffic/Wear Tolerance

Mean canopy color was significantly degraded by systematic wear treatment (Table 4). The main effect of wear treatment on independent canopy DGCI averaged 0.014 units. Canopy color response to the main plot wear treatment interacted with day after initiation (DAI), as well as liming agent treatment by DAI (Table 4) and is depicted in Figure 5A. Relative to the wear-treated control or limestone-treated plot having the lesser DGCI, the wear-treated plot receiving the Ca/Mg-SiO₃ split topdressings treatment showed significantly greater DGCI on four of the first six observation dates (Figure 5A). On the last two observation dates (287 and 296 DAI) in September 2011, the wear-treated plot receiving the Ca/Mg-SiO₃ split topdressings treatment showed significantly greater DGCI than the limestone-treated plots. Yet, in the second year (2012) on 613 and 648 DAI, the wear-treated plots receiving the semi-annual Ca/Mg-SiO₃ topdressing treatment showed significantly greater DGCI than the wear-treated control or limestone-treated plots having the lesser mean DGCI (Figure 5A). Only on 582 DAI did either the wear-treated control or limestone-treated plot register a mean DGCI value

significantly higher than the lowest mean DGCI recorded of plots topdressed by either Ca/Mg-SiO₃ treatment (Figure 5A).

Table 4. ANOVA of creeping bentgrass canopy dark green color index (DGCI) and density (normalized differential vegetative index, NDVI) by source.

Source	df	Canopy Color	Canopy Density
		<i>P</i> (F-ratio < F-crit)	
Wear	1	<0.001	<0.001
Liming agent treatment (LAT)	3	0.310	0.560
Wear × LAT	3	0.265	0.469
Day after initiation (DAI)	24	<0.001	<0.001
Wear × DAI	24	<0.001	<0.001
LAT × DAI	72	0.007	0.105
Wear × LAT × DAI	72	0.005	0.019

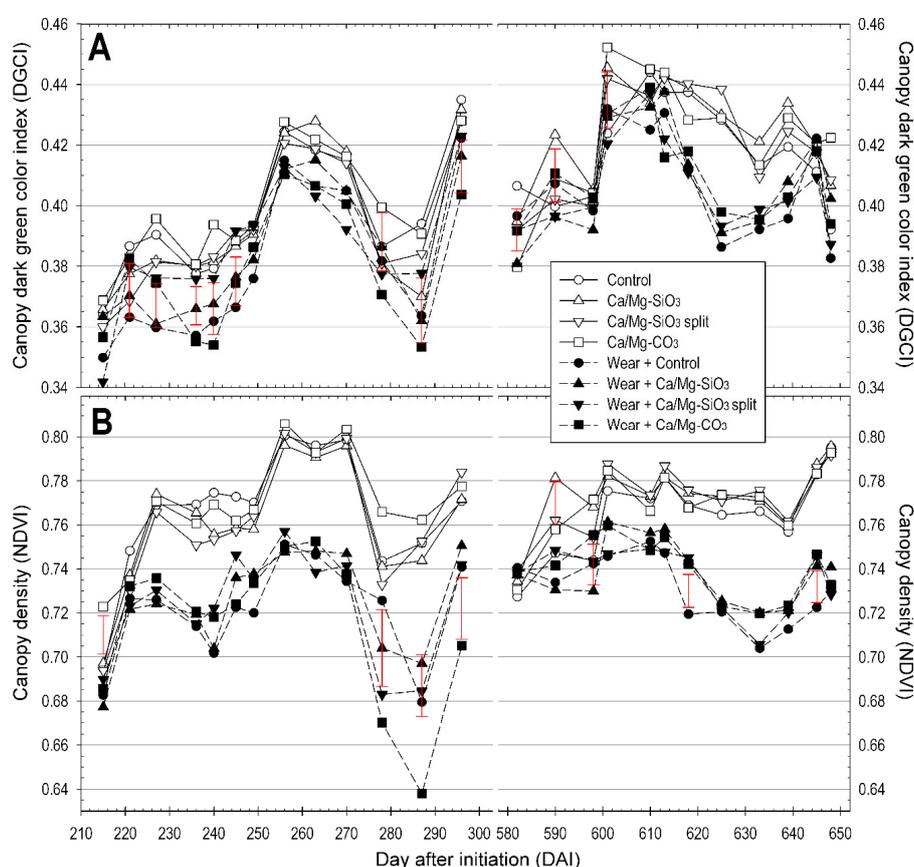


Figure 5. Creeping bentgrass (A) canopy dark green color index or (B) canopy density as influenced by the interaction of main-plot wear treatment, 2440 kg (ha year)⁻¹ liming agent treatment, and respective day after initiation (DAI). For DAI specified, error bars depict least significant difference (alpha = 0.05) between treatment combination means.

The main effect of wear treatment on independent canopy density indices equaled 0.038 NDVI units. Normalized difference vegetation index values (NDVI), or canopy density, of worn plots were observed in the 0.60 to 0.81 range, whereas non-trafficked canopy NDVI levels ranged from 0.67 to 0.82. Canopy density response to systematic wear treatment interacted with day after initiation (DAI), as well as liming agent treatment by DAI (Table 4). Canopy density response to liming agent and wear treatment by DAI is depicted in Figure 5B. Relative to the wear-treated limestone-topdressed plots, the wear-treated plots receiving the semi-annual Ca/Mg-SiO₃ topdressings showed significantly

greater NDVI on the last two observation dates (287 and 296 DAI) of 2011 (Figure 5B). On the previous observation date however (278 DAI), the wear-treated control plots registered a mean NDVI value significantly higher than the mean NDVI recorded of plots receiving split topdressings of Ca/Mg-SiO₃ (Figure 5B). Similarly, the wear-treated plots receiving the Ca/Mg-SiO₃ split topdressings treatment showed significantly greater NDVI than the control plots 618 and 645 DAI. However, the wear-treated plots receiving the semi-annual Ca/Mg-SiO₃ topdressing treatment showed a significantly lower mean NDVI than the limestone-treated plots 598 DAI (Figure 5B).

4. Discussion

4.1. Soil pH and Silicon Availability

Results showed that all liming agent treatments neutralized soil acidity and raised surface soil pH with equal effectiveness, despite the Ca/Mg-SiO₃ doing so to a lesser degree than recently reported [11]. Yet, the observed increase in extractable soil Si levels followed similar Si loading reactions described in recent evaluations of pelletized liming agent treatment [11–14]. For instance, just two months after incorporation into a silt loam soil having a 70 mg kg⁻¹ baseline Si concentration, application of 500 to 10,000 kg pelletized CaSiO₃ per hectare resulted in 40 to 330 mg kg⁻¹ increases in soil extractable silicon levels [11]. Having an initial soil level of 170 mg Si kg⁻¹, a mature tall fescue system in Kansas showed 2-year mean soil Si increases of 87 or 152 mg Si kg⁻¹ in response to split applications of pelletized CaSiO₃ totaling 0, 2.5, or 4.9 Mg CaSiO₃ per hectare annually [14].

Twenty-one months after initiating pelletized Ca/Mg-SiO₃ applications to a perennial ryegrass athletic field (baseline soil Si of 65 mg kg⁻¹), upper 16-cm soil differences in acetic-acid soil Si resulting from cumulative loads of 2440 or 3900 kg Ca/Mg-SiO₃ ha⁻¹ were only 22 or 46 mg Si kg⁻¹ greater than limestone-treated plots respectively [13]. Less than a half year later, the mean change in extractable Si at the exact soil depth was 38 or 73 mg kg⁻¹ greater than limestone-treated plots respectively [13]. Lastly, split applications totaling 0, 2440, or 4880 kg CaSiO₃ (ha year)⁻¹ to a creeping bentgrass putting green nursery resulted in approximately 2-year mean soil Si increases of 30 or 60 mg Si kg⁻¹ over the control plots [14]. To summarize, results of numerous field studies describing similar granular Ca/Mg-SiO₃ applications to a wide array of turfgrass systems in various climatic regions all show 0.5 M acetic acid extracts a seemingly unpredictable quantity of Si from treated soil.

These previous findings are consistent with the results of the present study. By 10 MAI, both Ca/Mg-SiO₃ treatments had been topdressed in full at the 2440 kg ha⁻¹ annual rate. Relative to the control plots, the 0- to 5-cm-deep soil Si levels in plots receiving the split or semi-annual Ca/Mg-SiO₃ topdressing regime increased only 6 or 9 mg Si kg⁻¹, respectively. Five months later (15 MAI), when 3660 kg Ca/Mg-SiO₃ ha⁻¹ had been cumulatively applied as split and semi-annual treatment regimes, these differences were 21 or 62 mg kg⁻¹, respectively. These results suggest the 0.5 M acetic acid soil extraction method accesses only a fraction of the Si present in soil-applied Ca/Mg-SiO₃ granules.

4.2. Turfgrass Vigor, Si Assimilation, Leaf H₂O Status, and Nutrition

Under the non-trafficked regiment and relative to plots receiving equal doses of plant-essential macronutrients, annual topdressing treatments of 2440 kg Ca/Mg-SiO₃ ha⁻¹ fostered 0.5 to 2.5 g kg⁻¹ mean leaf Si increases. The significant interaction of liming agent treatment and time on leaf Si concentration implicates a commingled influence of cumulative Ca/Mg-silicate topdressings and time elapsed since. Levels of the former were, depending on the treatment and sampling date; 0, 2200, 2440, 4636, or 4880 kg Ca/Mg-SiO₃ ha⁻¹. Likewise, levels of time elapsed since last Ca/Mg-SiO₃ topdressing were 0.25, 0.5, 1, 2, 2.5, 3, 4.5, and 5 months or 10, 11, 13, 22, and 24 months for the control or limestone-treated plots. The basis for which is the assured exclusion of silicate-containing products (excluding the described topdressings) from the experimental site beginning August 2010.

Stepwise regression of the full leaf Si sample set, by garden variety permutations of cumulative topdressing levels and months elapsed since, resulted in the following linear model describing 40.6% of observed variation with high statistical certainty; F-Ratio $_{2,96} = 32.8$ (Equation (1)):

$$\text{Leaf Si, g kg}^{-1} = 10.39 - 1.15 \sqrt{\begin{matrix} \text{months} \\ \text{elapsed} \\ \text{since} \\ \text{topdressing} \end{matrix}} - 0.0003 \left(\begin{matrix} \text{cumulative} \\ \text{Ca/Mg - SiO}_3 \\ \text{load, kg ha}^{-1} \end{matrix} \right) \quad (1)$$

For example, plots assigned either semi-annual or “split” Ca/Mg-SiO₃ treatment had received 2440 kg ha⁻¹ topdressing by September 2011 (10 MAI). Nevertheless, samples collected from plots receiving semi-annual Ca/Mg-SiO₃ topdressing were five months removed from SiO₃ inputs. Meanwhile, plots receiving the Ca/Mg-SiO₃ split treatment were topdressed only 2.5 months before the 10 MAI tissue sampling (albeit at a lesser rate). Similar circumstances preempted the June 2012 (19 MAI) clipping yield and leaf tissue analysis. Yet, despite more-recent split applications again in 2012, tissue Si levels in silicate-treated plots of either topdressing frequency were statistically equal. These described increases in leaf Si content agree closely with the published turfgrass results and confirm 0.3 to 4.5 g leaf Si kg⁻¹ increases following 1000 to 5000 kg pelletized Mg/Ca-SiO₃ ha⁻¹ applications in the field [12–17].

Ubiquity of Si in soil, along with disparate densities of dry leaf tissue or soil, justified measuring clipping yield and silicon concentration in samples collected from only non-trafficked plots. Yet this protective action admittedly presumes Si uptake and distribution across the turfgrass plant is independent of imposed wear stress. While subsequent growth chamber research results indicate tall fescue leaf tissue gains of approximately 1.4 g Si kg⁻¹ are induced just 4 weeks following imposed injury by metal file [37], further efforts toward field confirmation are warranted.

4.3. Turfgrass Traffic/Wear Tolerance

Direct field measures of creeping bentgrass mean canopy color or mean canopy density showed significant reduction resulted from systematic wear. Captured independently by two unique instruments (albeit of common origin, Spectrum Technologies, LLC), the otherwise sole computational element common to each index was 660-nm (red) reflectance. Resultantly, a significant direct correlation ($r = 0.607$, $p < 0.0001$) was observed among the 994 paired means of quadruplicate canopy DGCI and NDVI measures. Notwithstanding, and under either main plot wear treatment, no consistent reduction or improvement in mean canopy color or density resulted from liming agent treatment. While the highest order interaction (wear × LAT × DAI) was significant for both vegetation indices, lack of a significant LAT main effect implies the shuffling of treatment rank that occurred over the two growing seasons was without meaningful outcome.

For example, on twelve of the 25 sample dates, no significant differences in canopy DGCI were observed between liming agent treatment split-plots in either trafficked or non-trafficked main plots. However, either the worn or non-worn variety of the control or blended limestone treatment statistically exceeded one or both Ca/Mg-SiO₃ treatments receiving the same main plot wear treatment on five of the 13 dates DGCI differences were significant. Likewise, on 17 of the 25 sample dates, no significant differences in canopy density were observed between liming agent-treated split plots in either trafficked or non-trafficked main plots. However, on three of the eight dates the NDVI differences were significant, either the worn or non-worn variety of the control or blended limestone treatment statistically exceeded one or both Ca/Mg-SiO₃ treatments receiving the same main plot wear treatment. Thus, relative to blended limestone treatment or none and over 25 sample dates spanning two 3-month growing seasons in two consecutive years, topdressing Ca/Mg-SiO₃ at the described rate and frequency resulted in a net gain of 3 and 2 dates of statistically greater canopy color and density, respectively.

5. Conclusions

Beneficial effects of Si have been reported in a variety of plant species and environmental conditions. Recent evaluations of Si-rich liming agent and/or fertilizer treatment have shown highly varied assimilation and performance response by turfgrasses. When combined with imposed stress treatment(s), enhanced Si availability and uptake do not dependably foster statistically improved stress resistance of cool season turfgrass systems. Yet in specific regard to creeping bentgrass, the results of this study confirm the preponderance of inconclusive findings that currently command the scientific literature. In summary, increased Si offtake resulting from the described Si-rich liming agent treatments of a creeping bentgrass fairway did not significantly influence vigor, leaf H₂O content, or nutritional status. Furthermore, and regardless of imposed wear/traffic treatment, creeping bentgrass canopy color and density were similarly unaffected by increased Si in soil and leaf clippings of Ca/Mg-SiO₃-treated plots. If a critical leaf Si concentration threshold for enhanced creeping bentgrass wear tolerance exists, it is unlikely <11 g Si kg⁻¹.

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References

1. Poldervaart, A. Chemistry of the Earth's crust. *Geol. Soc. Am. Spec. Pap.* **1955**, *62*, 119–144.
2. Coskun, D.; Deshmukh, R.; Sonah, H.; Menzies, J.G.; Reynolds, O.; Ma, J.F.; Kronzucker, H.J.; Belanger, R.R. The controversies of silicon's role in plant biology. *New Phytol.* **2019**, *221*, 67–85. [[CrossRef](#)]
3. Sangster, A.G.; Hodson, M.J.; Tubb, H.J. Silicon deposition in higher plants. In *Silicon in Agriculture*; Elsevier Science: New York, NY, USA, 2001; pp. 85–113.
4. Gong, H.J.; Randall, D.P.; Flowers, T.J. Silicon deposition in the root reduces sodium uptake in rice (*Oryza sativa* L.) seedlings by reducing bypass flow. *Plant Cell Environ.* **2006**, *29*, 1970–1979. [[CrossRef](#)]
5. Soukup, M.; Martinka, M.; Cigán, M.; Ravaszová, F.; Lux, A. New method for visualization of silica phytoliths in *Sorghum bicolor* roots by fluorescence microscopy revealed silicate concentration-dependent phytolith formation. *Planta* **2014**, *240*, 1365–1372. [[CrossRef](#)] [[PubMed](#)]
6. Liang, Y.M.; Nikolić, M.; Bélanger, R.R.; Gong, H.; Song, A. *Silicon in Agriculture: From Theory to Practice*; Dordrecht-Springer: Dordrecht, The Netherlands, 2015; pp. 138–215.
7. Lux, A.; Luxová, M.; Abe, J.; Morita, S.; Inanaga, S. Silicification of bamboo (*Phyllostachys heterocycla* Mitf.) root and leaf. *Plant Soil* **2003**, *255*, 85–91. [[CrossRef](#)]
8. Guntzer, F.; Keller, C.; Poulton, P.R.; Mcgrath, S.P.; Meunier, J.-D. Long-term removal of wheat decreases soil amorphous silica at Broadbalk, Rothamsted. *Plant Soil* **2012**, *352*, 173–184. [[CrossRef](#)]
9. Korndorfer, G.H.; Snyder, G.H.; Ulloa, M.; Powell, G.; Datnoff, L.E. Calibration of soil and plant silicon analysis for rice production. *J. Plant Nutr.* **2001**, *24*, 1071–1084. [[CrossRef](#)]
10. Barbosa-Filho, M.P.; Snyder, G.H.; Elliot, C.L.; Datnoff, L.E. Evaluation of soil test procedures for determining rice-available silicon. *Commun. Soil Sci. Plant Anal.* **2001**, *32*, 1779–1792. [[CrossRef](#)]
11. Nanayakkara, U.N.; Uddin, W.; Datnoff, L.E. Application of silicon sources increases silicon accumulation in perennial ryegrass turf on two soil types. *Plant Soil* **2008**, *303*, 83–94. [[CrossRef](#)]

12. Datnoff, L.E.; Rutherford, B.A. Accumulation of silicon by bermudagrass to enhance disease suppression of leaf spot and melting out. *USGA TERO* **2003**, *2*, 1–8.
13. Pruyne, D.P.; Schlossberg, M.J.; Uddin, W. Perennial ryegrass wear resistance and soil amendment by Ca and Mg-silicates. *Agronomy* **2019**, *9*, 578. [[CrossRef](#)]
14. Zhang, Q.; Fry, J.; Lowe, K.; Tisserat, N. Evaluation of calcium silicate for brown patch and dollar spot suppression on turfgrasses. *Crop Sci.* **2006**, *46*, 1635–1643. [[CrossRef](#)]
15. Bae, E.J.; Kim, C.Y.; Yoon, J.H.; Lee, K.S.; Park, Y.B. Effect of silicate fertilizer application on zoysiagrass (*Zoysia japonica* Steud.) field. *Weed Turfgrass Sci.* **2018**, *7*, 247–257. [[CrossRef](#)]
16. Trenholm, L.E.; Duncan, R.R.; Carrow, R.N.; Snyder, G.H. Influence of silica on growth, quality, and wear tolerance of seashore paspalum. *J. Plant Nutr.* **2001**, *24*, 245–259. [[CrossRef](#)]
17. Redmond, C.T.; Potter, D.A. Silicon fertilization does not enhance creeping bentgrass resistance to cutworms and white grubs. *Appl. Turfgrass Sci.* **2006**. [[CrossRef](#)]
18. Uriarte, R.F.; Shew, H.D.; Bowman, D.C. Effect of soluble silica on brown patch and dollar spot of creeping bentgrass. *J. Plant Nutr.* **2004**, *27*, 325–339. [[CrossRef](#)]
19. Barber, S.A. Liming materials and practices. In *Soil Acidity and Liming*, 2nd ed.; Agron. Monogr. 12; ASA, CSSA, and SSSA: Madison, WI, USA, 1984; pp. 171–209.
20. Schlossberg, M.J.; Waltz, F.C.; Landschoot, P.J.; Park, B. Recent mechanical cultivation of lawns enhances lime application efficacy. *Agron. J.* **2008**, *100*, 855–861. [[CrossRef](#)]
21. Soukup, M.; Martinka, M.; Bosnic, D.; Caplovicová, M.; Elbaum, R.; Lux, A. Formation of silica aggregates in sorghum root endodermis is pre-determined by cell wall architecture and development. *Ann. Bot.* **2017**, *120*, 739–753. [[CrossRef](#)]
22. Canaway, P.M. Wear tolerance of turfgrass species. *J. Sports Turf Res. Inst.* **1981**, *57*, 65–83.
23. Beard, J.B. *Turfgrass Science and Culture*; Prentice Hall: Englewood Cliffs, NJ, USA, 1973; pp. 368–465.
24. He, C.; Wang, L.; Liu, J.; Liu, X.; Li, X.; Ma, J.; Lin, Y.; Xu, F. Evidence for ‘silicon’ within the cell walls of suspension-cultured rice cells. *New Phytol.* **2013**, *200*, 700–709. [[CrossRef](#)]
25. Suzuki, S.; Ma, J.F.; Yamamoto, N.; Hattori, T.; Sakamoto, M.; Umezawa, T. Silicon deficiency promotes lignin accumulation in rice. *Plant Biotechnol.* **2012**, *29*, 391–394. [[CrossRef](#)]
26. Yamamoto, T.; Nakamura, A.; Iwai, H.; Ishii, T.; Ma, J.F.; Yokoyama, R.; Nishitani, K.; Satoh, S.; Furukawa, J. Effect of silicon deficiency on secondary cell wall synthesis in rice leaf. *J. Plant Res.* **2012**, *125*, 771–779. [[CrossRef](#)] [[PubMed](#)]
27. Kido, N.; Yokoyama, R.; Yamamoto, T.; Furukawa, J.; Iwai, H.; Satoh, S.; Nishitani, K. The matrix polysaccharide (1;3,1;4)-b-d-glucan is involved in silicon dependent strengthening of rice cell wall. *Plant Cell Physiol.* **2015**, *56*, 268–276. [[CrossRef](#)] [[PubMed](#)]
28. Kaur, H.; Gregor, M. A review on Si uptake and transport system. *Plants* **2019**, *8*, 81. [[CrossRef](#)] [[PubMed](#)]
29. Cockerham, S.T.; Brinkman, D.J. A simulator for cleated-shoe sports traffic on turfgrass research plots. *Calif. Turfgrass Cult.* **1989**, *39*, 9–12.
30. Zhu, Q.; Schlossberg, M.J.; Bryant, R.B.; Schmidt, J.P. Creeping bentgrass putting green response to foliar nitrogen fertilization. *Agron. J.* **2012**, *104*, 1589–1594. [[CrossRef](#)]
31. Schlossberg, M.J.; Karnok, K.J.; Landry, G. Estimation of viable root length density of heat-tolerant creeping bentgrass cultivars, ‘Crenshaw’ and ‘L93’, by an accumulative degree day model. *J. Am. Soc. Hort. Sci.* **2002**, *127*, 224–229. [[CrossRef](#)]
32. Zhu, Q.; Schlossberg, M.J.; Bryant, R.B. Foliar fertilization-induced injury and recovery of a creeping bentgrass putting green. *J. Plant Nutr.* **2016**, *39*, 1589–1596. [[CrossRef](#)]
33. Moody, D.R.; Schlossberg, M.J.; Archibald, D.D.; McNitt, A.S.; Fidanza, M.A. Soil water repellency development in amended sand rootzones. *Crop Sci.* **2009**, *49*, 1885–1892. [[CrossRef](#)]
34. Guntzer, F.; Keller, C.; Meunier, J.D. Determining silicon concentration in plant material using Tiron extraction. *New Phytol.* **2010**, *188*, 902–906. [[CrossRef](#)]
35. Karcher, D.E.; Richardson, M.D. Quantifying turfgrass color using digital image analysis. *Crop Sci.* **2003**, *43*, 943–951. [[CrossRef](#)]
36. Carrow, R.N.; Waddington, D.V.; Rieke, P.E. *Turfgrass Soil Fertility and Chemical Problems: Assessment & Management*; Wiley & Sons: Hoboken, NJ, USA, 2001; pp. 16–348.

37. McLarnon, E.; McQueen-Mason, S.; Lenk, I.; Hartley, S.E. Evidence for active uptake and deposition of Si-based defenses in tall fescue. *Front. Plant Sci.* **2017**, *8*, 1199. [[CrossRef](#)] [[PubMed](#)]



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