



## Article

# Creeping Bentgrass Nutritional, Morphological, and Putting Green Performance Response to Ca/Mg-Silicate Slag Liming Agent

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**Abstract:** While not classified as an essential plant nutrient, silicon (Si) assimilation following exogenous Si application has enhanced the wear resistance of cool-season turfgrass. Given this beneficial supplementation of lignin by Si reported in epidermal tissue of monocotyledonous plants, our research objective was to quantify root morphology, vegetative nutrition and vigor, soil chemistry, and putting green performance in response to split applications of pelletized liming agents rich in Si and/or Ca and Mg. Field evaluation of granular liming agent treatment, 2441 kg (ha year)<sup>-1</sup>, was conducted on creeping bentgrass (*Agrostis stolonifera* L. cv. Penn G-2) putting green maintained in the Mid-Atlantic US. Pelletized Ca/Mg-SiO<sub>3</sub> slag or dolomitic limestone treatments were conducted in frequent split applications and incorporated into the upper 5 cm of the rootzone. Measurements of canopy color and density, shoot growth as clipping yield, soil pH, Si and nutrient content of clippings, and soil extractable Si were performed each season. Cumulative Ca/Mg-SiO<sub>3</sub> application (kg ha<sup>-1</sup>) increased mean acetic acid (HOAc) extractable Si by 35 to 60 mg kg<sup>-1</sup> and leaf Si content by 1.0 to 1.5 mg g<sup>-1</sup>. However, neither putting green canopy quality, shoot nutrient concentration, 5 to 15 cm depth root length density nor ball roll distance was improved by liming agent treatment. Liming agent-treated or untreated plots showed statistical, yet inconsistent, differences in clipping yield 4, 14, 15, 16, and 17 months from initiation (MFI). This thorough shuffling of treatment rank, resulting in identical experiment-wide means precludes the expectation of dependably superior vigor by any.



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**Keywords:** canopy color; canopy density; green speed; nutrition; root length density; shoot growth; silicic acid; silicon; turfgrass

## 1. Introduction

Silicon (Si) is a predominant component of both the earth's crust and soil minerals [1]. Although Si is not categorized as a required plant nutrient, Si uptake results in apoplastic deposition across the epidermal and cuticular tissue of shoots and exodermal and endodermal tissue of roots [2–5]. Plant assimilation, particularly by monocots, has been identified as the primary cause of Si depletion from shallow soil depths [6,7].

Foliar treatment of creeping bentgrass (*Agrostis stolonifera* L.) by liquid Si fertilizer increased shoot tissue Si levels in Kentucky [8], but not in North Carolina [9]. Soil amendment through incorporation or topdressing of Ca- and/or Mg-SiO<sub>3</sub> granules has been reported to prompt significant Si accumulation in shoot tissue of resident creeping bentgrass, tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.), and perennial ryegrass (*Lolium perenne* L.) [10,11]. Results of a 7-week greenhouse study discounted leaf Si concentration but showed increased leaf cellulose, lignin, and superoxide dismutase content as well as significantly enhanced wear resistance of Kentucky bluegrass (*Poa pratense* L.) 15 to 45 d following Si fertilizer treatment [12]. In combination with weekly wear treatments in the field, Ca/Mg-SiO<sub>3</sub> topdressing at a 2440 kg (ha year)<sup>-1</sup> rate significantly improved mean canopy density (normalized differential vegetative index, NDVI) of perennial ryegrass but not of creeping bentgrass maintained as a golf course fairway [13,14].

Ca/Mg-silicate ( $\text{SiO}_3$ ) slag is a dense, finely textured, granular by-product of steel fabrication and processing. Having a calcium carbonate equivalency of 500 to 850  $\text{g kg}^{-1}$ , Ca/Mg- $\text{SiO}_3$  reuse in cement and agricultural limestone products proves cost-effective when sourced locally [15,16]. Neutralization of soil exchangeable acidity by typical carbonate, hydroxy-, or oxide-based lime sources produces  $\text{CO}_2$  or  $\text{H}_2\text{O}$ , respectively. However, acid neutralization by Ca/Mg- $\text{SiO}_3$  generates silicic acid,  $\text{H}_4\text{SiO}_4$  [14]. This slightly soluble silicate form is dependably assimilated by plant roots and distributed to cuticular, vascular, and epidermal tissues [4,17].

Ball roll distance, i.e., green speed, is an impermanent putting green trait, highly regarded by accomplished golfers and consequently sought by golf course superintendents. Inversely proportional to surface resistance (friction), green speed is typically increased by frequent mowing at a low height of cut and further culture supporting an upright growth habit and a firm, smooth, dry surface [18]. Despite promotion by industry vendors, evidence of ball roll response to exogenous silica treatment is absent from the literature.

Creeping bentgrass is classified as a Si accumulator [19], and silicic acid deposition in monocotyledonous stalk tissue is reported to impart structural resilience by apoplastic obstruction [2]. Furthermore, silicic acid accumulation has been shown to supplant lignin without affecting resistance to applied compressive force [20–22]. Thus, the objective of the field research was to quantify creeping bentgrass putting green morphological and performance response to split application of a pelletized  $\text{SiO}_3$ -rich liming agent.

## 2. Materials and Methods

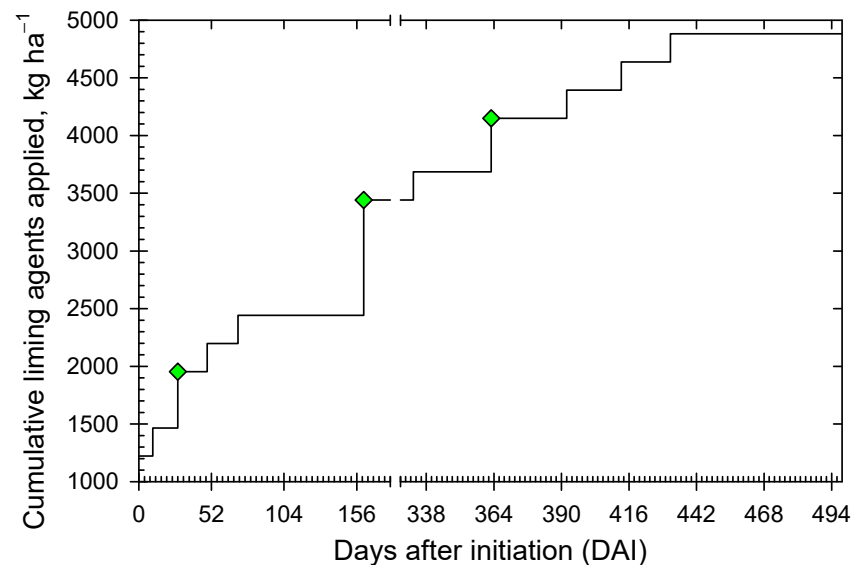
The field study was initiated on a ‘Penn G2’ creeping bentgrass putting green maintained within the Joseph Valentine Turfgrass Research Center (University Park, PA, USA). Using a 2 cm id hollow-core soil punch, the putting green rootzone was sampled from the 0 to 15 cm depth on 2 April. A composite sample was submitted to Penn State University Agricultural Analytical Services Lab (PSU-AASL) for 1:1 (by mass) soil:deionized water ( $\text{DI H}_2\text{O}$ ) soil pH and Mehlich-3 exchangeable Ca, K, and Mg, and extractable P, S, Cu, and Zn fertility analysis.

The employed experimental arrangement was a randomized complete block design (RCBD). Four identical blocks were situated over the level-most putting green surface and comprised three plots each ( $1.2 \times 4.3$  m, 0.2 m borders). The fifth block, situated on a gently sloping surface and comprising three (3) plots ( $0.91 \times 1.8$  m, 0.3 m borders), was treated identically to the four larger blocks. All dependent variable measures except for ball roll distance were collected from the smaller fifth block. The following liming agents were randomly assigned to a plot in each block: 2441  $\text{kg (ha year)}^{-1}$  of pelletized Ca/Mg- $\text{SiO}_3$  (Harsco Minerals Intl., Sarver, PA, USA) or a positive control treatment of pelletized  $\text{CaMg}(\text{CO}_3)_2$  (Oldcastle Lawn & Garden, Thomasville, PA, USA). Liming agents were applied by hand shakers and the guaranteed analysis of each exists in published records [13]. The third plot in each block was left untreated as a negative control.

### 2.1. Chronology of Treatment Applications, Soil Sampling, and Methods of Soil Analysis

Initial rates of 1221  $\text{kg ha}^{-1}$  liming agent were applied on 21 April (Figure 1). An additional 244  $\text{kg ha}^{-1}$  was applied on 1 May. Granule diameter, ranging from 0.8 to 2.3 mm, prevented complete penetration of the canopy. While mowing was easily withheld at this time, any mowing frequency other than daily between May and September would not satisfy the performance expectations of modern golf course clientele. Thus, on 18 May, the putting green was core-aerified to an approx. 7 cm depth using 1 cm diameter solid tines on 5 cm centers. The following day, liming agent treatments were applied at a 488  $\text{kg ha}^{-1}$  rate, brushed into the aerification holes, and irrigated with 1 cm potable water (Figure 1). Beginning 23 May, the putting green was mowed  $6 \pm 1$  d each week at a 3.2 mm height of cut. Maintenance fertilization comprised semi-monthly foliar applications of urea, sulfate of potash, and micronutrient fertilizers to support plant availability of approx. 20 kg N, 10 kg K, 8 kg S, 3 kg Fe, and 1 kg Mn  $\text{ha}^{-1}$  each growing month. An additional 244  $\text{kg ha}^{-1}$

of the liming agent was applied on 9 June and 1 July (Figure 1), each followed by either irrigation or a rainfall event, and mowing was suspended for 1 or 2 days.



**Figure 1.** Cumulative mass of pelletized liming agents applied by days after initiation (DAI). Green diamonds denote applications incorporated into aerification holes.

Using the described 2 cm id soil punch and avoiding aerification holes from the May coring, duplicate samples of the 0 to 15 cm depth were collected from each plot on 27 July (3 months following initiation, MFI). The 0 to 5 cm depth segment of each was discarded and the 5 to 15 cm segments were combined.

Triplicate soil samples of 0–15 cm depth were collected from each plot in September (5 MFI). Collected soil cores were divided into 0 to 5, 5 to 10, and 10 to 15 cm depth segments, dried, and ground to pass a 1 mm sieve. Sieved depth segments were split for PSU-AASL soil pH and Mehlich-3 fertility analysis or 0.5 M acetic acid (HOAc) extraction and analysis of plant-available soil Si [23] by ICP-OES (Optima 7300dv, Perkin Elmer Inc., Hebron, KY, USA).

On 29 September, the putting green was core-aerified as previously described. Liming agent treatments ( $1000 \text{ kg ha}^{-1}$ ) were applied, carefully brushed into the evacuated holes, and irrigated (1 cm). An additional  $244 \text{ kg ha}^{-1}$  of each respective granular agent was applied the following spring (19 March).

While avoiding core-aerification holes, triplet soil samples were diligently collected from the 0 to 15 cm depth of each plot on 18 April (12 MFI). Using a ruler and knife, soil cores were divided into three 5 cm segments, dried, ground to pass a 1 mm sieve, and analyzed for HOAc extractable-Si and Mehlich-3 nutrients as described. Meanwhile, the putting green was core-aerified (as described) and treated with  $465 \text{ kg ha}^{-1}$  of the respective granular treatment. Granules were carefully brushed into the tine holes and the putting green was irrigated (1 cm). An additional  $244 \text{ kg ha}^{-1}$  of the respective liming agent treatment granules was applied on 17 May, 7 June, and 26 June, and the putting green was again irrigated (0.5 cm). Mowing was suspended the morning following each application.

Quadruplicate samples were collected from the 0 to 15 cm soil depth of each plot on 31 August (16 MFI). Soil cores were promptly divided into 0 to 5 cm and 5 to 15 cm depth segments. Two 5 to 15 cm segments were randomly pooled for preparation and analysis of root length. The remaining 5 to 15 cm segments were segmented at the 10 cm depth. All remaining 0 to 5 cm, 5 to 10 cm, and 10 to 15 cm segments were pooled, sieved, split, and analyzed for soil pH and Mehlich-3 or HOAc extractable Si as previously described.

## 2.2. Field Assessment of Putting Green Canopy and Performance

Every  $10 \pm 7$  days each season, canopy reflectance was collected in triplicate using commercial instruments described by Pruyne et al. [14]. Recorded reflectance values were used to calculate the normalized differential vegetative (NDVI) and dark green color indices (DGCi), quantitative and resolute measures of canopy density and color, respectively [24,25]. Ball roll distance was measured on the four level blocks using a PELZmeter [26]. The mean of six ball rolls, three in either direction along the 4.3 m length of each plot, was recorded in June, July, August, and September of each growing season.

## 2.3. Laboratory Analysis of Plant Roots and Vegetation

A total of 5 to 15 cm depth soil cores sampled 3 or 16 MFI were eluted of sand/soil and the roots were stained in neutral red for 24 h [27]. The stained roots were thoroughly rinsed before being suspended in a water-filled plexiglass tray and then transmissively scanned at 1800 dpi resolution. Binary tag image file formats (.TIFF) were generated for root length density measurement by winRHIZO image analysis software (Regent Instrument Inc., Quebec City, QC, Canada), as described by Bouma et al. [27].

Following purposeful 2- to 3-day mowing ‘respites,’ clipping yields were collected from all plots monthly. Immediately following the four collections conducted each growing season, clipping yields were dried (70 C) and weighed to a tenth of a milligram resolution [28]. Given the dense, sparingly soluble, and nutrient-rich nature of the pelletized liming agent granules, concern for liming agent residue contamination precluded tissue analysis of Si [6] or essential plant nutrients [14] in yields collected less than three weeks after granular treatments were applied. Thus, while eight repeated measures of clipping yield were collected (and reported), only five repeated measures of silicon and nutrient concentration were reported. Silicon uptake was determined on a per plot basis as described [14].

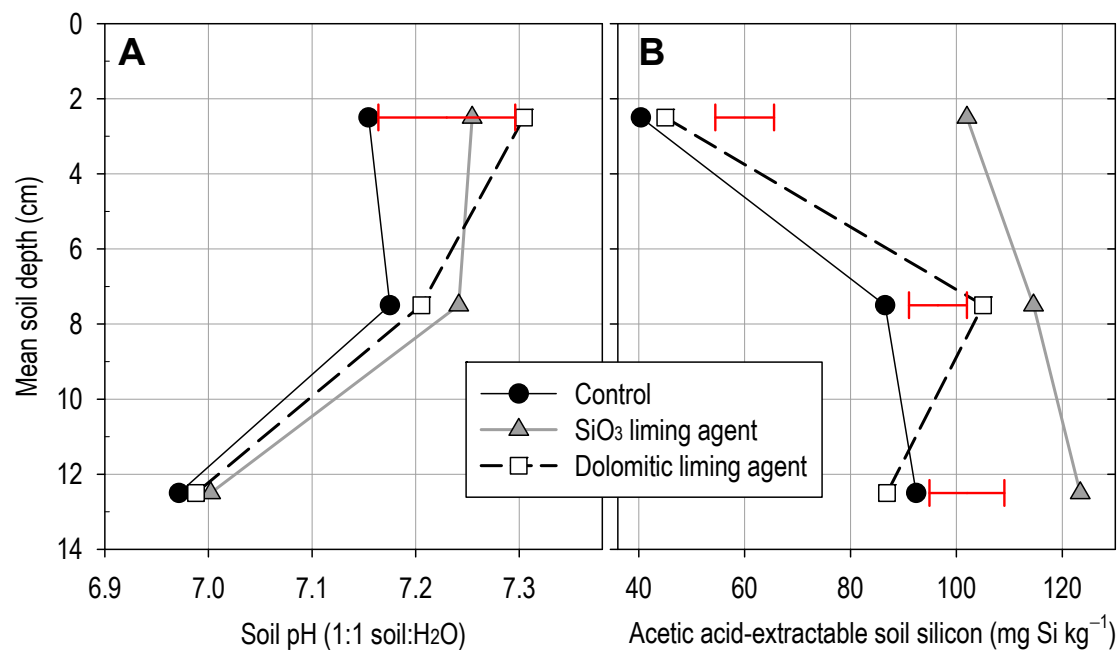
## 2.4. Statistical Analysis

All data were analyzed as a split plot in a randomized complete block design. Soil pH and plant-available soil Si levels were sorted by depth before being modeled by treatment using PROC MIXED (SAS Institute, v. 8.2, Cary, NC, USA). The main plot effect of liming agent treatment on soil pH, soil Si, canopy color, canopy density, ball roll distance, root length density, clipping yield, leaf Si content, Si uptake, or tissue nutrient concentration was F-tested by its block interaction term (df = 6 for ball roll distance, 8 for all other dependent variables). Longitudinal effects and their interaction with TRT were analyzed using time-series covariate structures and F-tested by the residual error. Model diagnostics identified outliers for satisfaction of constant variance, error independence, and normal distribution of error ANOVA assumptions. These outliers were omitted, rather than replaced, yet they never comprised more than 1% of dependent variable observations. All main effect and interaction hypothesis tests employed two-tailed separation of treatment means by Fisher’s protected least significant difference (LSD) at the 0.05 alpha level.

# 3. Results and Discussion

## 3.1. Soil Chemistry, Fertility, and Extractable Si

The main effect of treatment influence on mean soil pH was limited to the 0 to 5 cm soil depth ( $p < 0.05$ ). Averaged over the three (3) soil sampling events (5, 12, and 16 MFI) and relative to untreated plots, only dolomitic limestone treatment significantly raised the mean pH in the upper 0 to 5 cm deep soil segment (Figure 2A). This likely resulted from the greater acid-neutralizing power of dolomitic limestone ( $940 \text{ g kg}^{-1} \text{ CaCO}_3 \text{ equiv.}$ ) relative to the pelletized  $\text{SiO}_2$  liming agent ( $790 \text{ g kg}^{-1} \text{ CaCO}_3 \text{ equiv.}$ ) treatment [13]. Regardless of treatment, the mean soil pH level in the 10 to 15 cm soil depth of all plots was lower than levels observed at shallower depths.



**Figure 2.** Mean (A) soil pH (1:1 soil:DI H<sub>2</sub>O) or (B) HOAc extractable silicon, by treatment and sampling depth. Each symbol represents five (5) replications pooled over three (3) sampling dates ( $n = 15$ ). At the depth(s) shown, the red horizontal error bars represent Fisher's protected least significant difference ( $\alpha = 0.05$ ) between liming agent treatments.

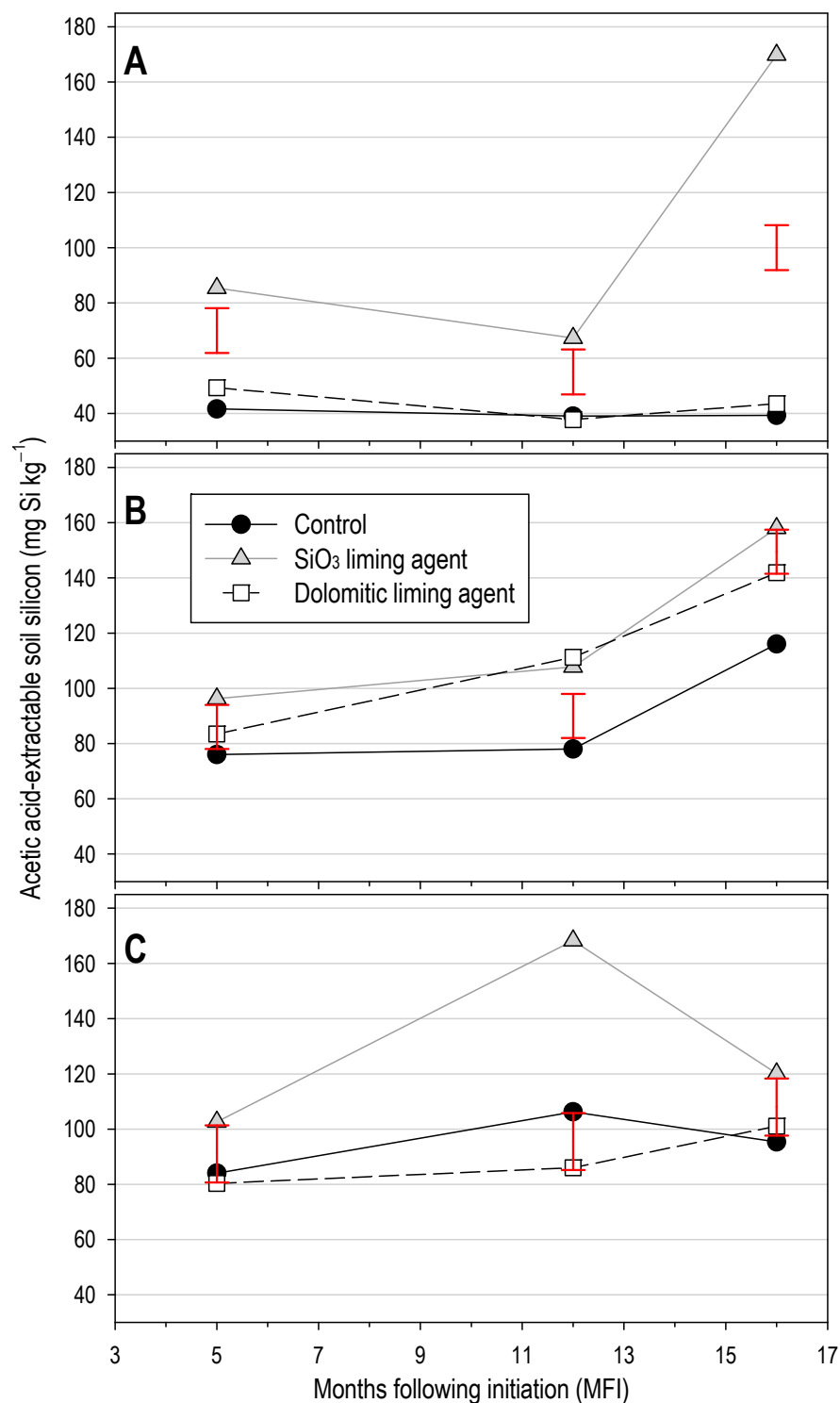
The 0.5 M HOAc extraction quantified availability of silica more dependably than Mehlich-3. Relative to untreated plots, SiO<sub>3</sub> liming agent treatment significantly increased mean HOAc extractable Si ( $p < 0.05$ ) in every soil depth segment (Figure 2B). The extractable soil silicon level in the control (untreated) plots was the lowest in the soil surface segment (0 to 5 cm) and increased with depth (Figure 2B). Relative to limestone-treated or untreated plots, SiO<sub>3</sub> liming agent treatment significantly increased 0 to 5 cm deep mean extractable Si by approximately 60 mg Si kg<sup>-1</sup>. While of lesser magnitude, similar results were observed in the 1 to 5 cm soil depth following SiO<sub>3</sub> liming agent treatment of a slightly acidic creeping bentgrass fairway [13]. The greater mean extractable Si response in the upper 5 cm of the putting green to equivalent SiO<sub>3</sub> liming agent treatment rate is likely the result of cultivation-facilitated soil incorporation—i.e., SiO<sub>3</sub> liming agent was simply broadcast over plots of the fairway study.

Regardless of treatment and relative to the adjacent surface soil, greater mean extractable Si was observed in the 5 to 10 cm soil depth (Figure 2B). Likewise, the dolomitic or SiO<sub>3</sub> liming agent significantly increased mean extractable Si relative to the alternative in this 5 to 10 cm soil depth segment (Figure 2B). While a significant departure from the published creeping bentgrass fairway response to similar rates of identical liming agents, this could have resulted from the incorporation of the liming agents into the putting green rootzone [13].

The higher soil pH in the putting green rootzone may have also proved influential, as the aqueous solubility of silicic acid solubility correlates directly to soil solution pH [4,29]. For many of the same reasons described above, elevated mean levels of extractable Si were observed in the deepest sampled soil depth, and significantly high levels were observed in plots treated by SiO<sub>3</sub> liming agent (Figure 2B).

Throughout the experimental duration, Mehlich-3 extractable levels of soil phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) were the greatest at the surface of the putting green. Soil macronutrient levels throughout the upper 15 cm profile of all plots were supportive of both annual bluegrass and creeping bentgrass requirements and did not significantly vary by treatment in any soil depth segment.

Sample date, as months following initiation (MFI), interacted with liming agent treatment to significantly influence HOAc extractable Si ( $p < 0.05$ ) in every soil depth segment (Figure 3). Relative to untreated control plots,  $\text{SiO}_3$  liming agent application significantly increased soil extractable Si in every soil depth segment and sampling date except in the 10 to 15 cm soil depth 5 MFI (Figure 3C).



**Figure 3.** Mean acetic acid-extractable soil Si by treatment and collection date for the (A) 0 to 5 cm, (B) 5 to 10 cm, or (C) 10 to 15 cm sampling depth. Mean values displayed are pooled over five (5) replicates. Within any depth segment and month following initiation (MFI), red vertical error bars represent the least significant difference ( $\alpha = 0.05$ ) between liming agent treatments.



No significant differences in extractable soil Si were observed between untreated and dolomitic-liming-agent-treated plots at any MFI in the 0 to 5 cm or 10 to 15 cm sampling depths (Figure 3A,C). However, extractable soil Si significantly exceeding untreated plots was observed in the 5 to 10 cm soil depth of dolomitic and SiO<sub>3</sub> liming agent-treated plots, 12 and 16 MFI (Figure 3B).

Similar 0 to 5 cm soil depth response was reported in a like-treated creeping bentgrass fairway, except that approximately 10 mg Si kg<sup>-1</sup> more of HOAc extractable Si was observed in untreated or dolomitic lime-treated putting green plots than like-treated plots in the fairway study [13]. Moreover, 40 to 70 mg more extractable Si kg<sup>-1</sup> soil was measured in the 0 to 5 cm soil segment of SiO<sub>3</sub> liming agent-treated putting green plots than their fairway counterparts.

### 3.2. Clipping Vigor and Nutrition and Canopy Color and Density

The mean clipping yield pooled over four summer months and two consecutive growing seasons was unaffected by treatment (Table 1). Only one publication describing creeping bentgrass putting green response to SiO<sub>3</sub> fertilization in the field reports clipping yield. The clipping yield results observed herein confirm those of Uriate et al. [9] who, over two growing seasons, saw no significant clipping yield response of either Pennncross or a Cato:Crenshaw blend to semi-monthly treatment by soluble potassium silicate (20.7% SiO<sub>2</sub>) at 25 or 50 kg SiO<sub>2</sub> ha<sup>-1</sup>.

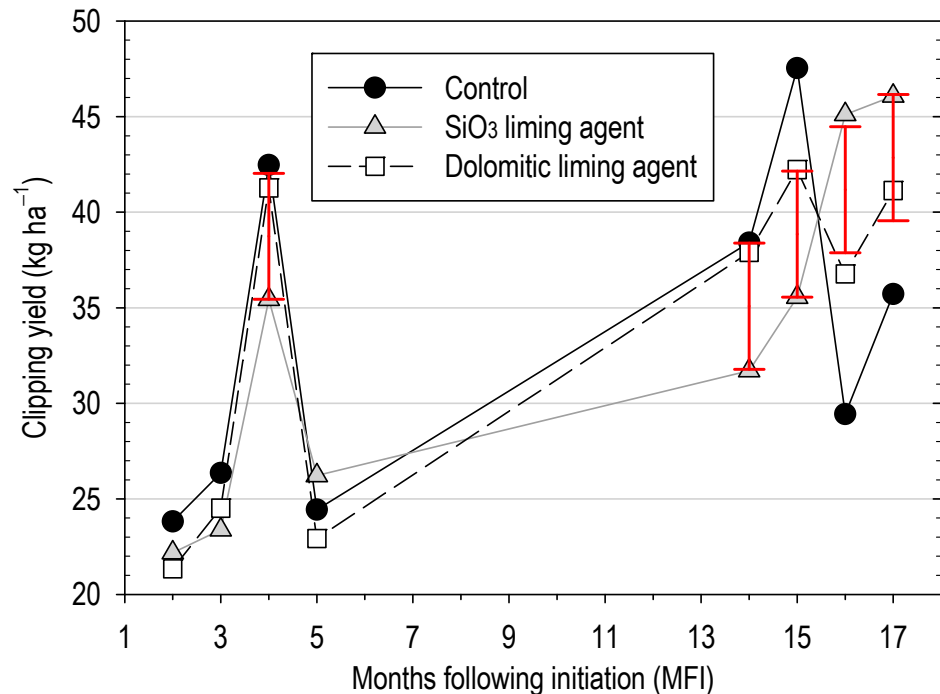
**Table 1.** Global analysis of variance by dependent variable and source, liming agent treatment (TRT) means, and associated Fisher's protected least significant differences ( $\alpha = 0.05$ ).

Dependent Variable, Units	Source				Liming Agent TRT Means			
	TRT	Time	TRT $\times$ Time	<i>n</i>	Control	Ca/Mg-SiO <sub>3</sub>	Ca/Mg-CO <sub>3</sub>	LSD5%
	<i>p</i> (F > Fcrit)							
Clipping yield, kg ha <sup>-1</sup>	ns <sup>1</sup>	**	**	40	33.5	33.2	33.5	–
Canopy color, DCGI	ns	*	ns	170	0.403	0.406	0.402	–
Canopy density, NDVI	ns	*	ns	170	0.748	0.746	0.746	–
Ball roll distance, m	ns	*	ns	32	2.66	2.64	2.66	–
Leaf Si, mg g <sup>-1</sup>	**	**	ns	25	4.78	6.29	5.22	0.60
Si uptake, g ha <sup>-1</sup>	**	**	ns	25	156	220	173	33
Leaf K, mg g <sup>-1</sup>	ns	**	ns	25	20.0	19.8	20.0	–
Leaf P, mg g <sup>-1</sup>	*	*	ns	25	6.5	6.5	6.3	0.2
Leaf Ca, mg g <sup>-1</sup>	ns	*	ns	25	6.0	6.2	6.0	–
Leaf Mg, mg g <sup>-1</sup>	ns	*	ns	25	2.7	2.7	2.7	–
Leaf S, mg g <sup>-1</sup>	*	*	ns	25	5.0	5.0	4.8	0.2
Leaf Fe, µg g <sup>-1</sup>	ns	*	ns	25	594	560	680	–
Leaf Mn, µg g <sup>-1</sup>	ns	*	ns	25	73	69	75	–
Leaf Zn, µg g <sup>-1</sup>	ns	*	ns	25	41	42	41	–
Leaf B, µg g <sup>-1</sup>	ns	*	ns	25	20	20	20	–
5 to 15 cm soil depth								
Root length density, cm cm <sup>-3</sup>	ns	*	ns	10	4.33	3.86	4.08	–

\*, \*\*: significant at the 0.05 and 0.01 probability levels, respectively. <sup>1</sup> ns: not significant.

The treatment-by-time interaction signifies an effect on clipping yield (Table 1), with most treatment differences occurring in the second study year (Figure 4). Despite this, there was no consistent outperformer in the second year. Regarding yield comparison between the liming agents, the dolomitic lime fostered greater yield than the SiO<sub>3</sub> liming agent 15 MFI. The opposite was observed at 16 MFI, and no yield differences between the two liming agents were observed at any other MFI (Figure 4). Likewise, a difference in yield between the dolomitic lime and control treatment was observed at only 16 MFI. Conversely, the yield of the control treatment significantly exceeded that of the SiO<sub>3</sub> treatment 4, 14, and 15 MFI, whereas the alternative was true 16 and 17 MFI (Figure 4). The absence of

a significant liming agent treatment main effect, even when accompanied by a shuffling of treatment rank over repeated measures, often justifies a global ANOVA. The planned treatments did not dependably govern creeping bentgrass putting green vigor and shoot growth over the described experimental conditions.



**Figure 4.** Cohabited putting green clipping yield by treatment and months following initiation (MFI). Mean values displayed are pooled over five (5) replicates. At indicated MFI, red error bars represent Fisher's protected least significant difference ( $\alpha = 0.05$ ) between liming agent treatments.

Mean canopy color or density response was not significantly influenced by either the main effect of liming agent treatment or treatment by sample date interaction (Table 1). This lacking response confirms earlier reports of nonsignificant influence on visual canopy quality from foliar or granular SiO<sub>2</sub> treatment of creeping bentgrass putting greens in the field [9,11].

A few main effects of liming agent treatment on bentgrass canopy nutrition were observed (Table 1). The dolomitic liming agent treatment resulted in significantly lesser mean leaf P and S than all others (Table 1), yet the observed mean leaf P and S levels far exceeded each deficiency threshold referenced for creeping bentgrass and annual bluegrass [30]. A negative correlation between the rate of granular SiO<sub>3</sub> liming agent application and creeping bentgrass putting green leaf P reported may have been due to the associated increase in soil pH from 7.2 to 7.9 [11]. Liming agent treatment did not interact with the sampling date to influence bentgrass canopy nutrition (Table 1).

The SiO<sub>3</sub> liming agent uniquely contained 18 g Fe and 5 g Mn kg<sup>-1</sup> [14], thus compelling our frequent maintenance fertilization of these two important micronutrients. Accordingly, mean leaf Fe or Mn level was unaffected by treatment and observed within the respective sufficiency range of each (Table 1). In fact, all observed mean concentrations of the analyzed essential nutrients fell within sufficiency ranges for creeping bentgrass [30]. Given the critical threshold for K in annual bluegrass tissue exceeds that of creeping bentgrass and most other cool-season grasses [31], the observed mean K levels (Table 1) may arguably be approaching their critical deficiency threshold. However, the timing of response variable collection precluded the influence of artifactual winter injury and tissue K was unaffected by the employed treatments (Table 1).



### 3.3. Silicon Uptake and Leaf Content

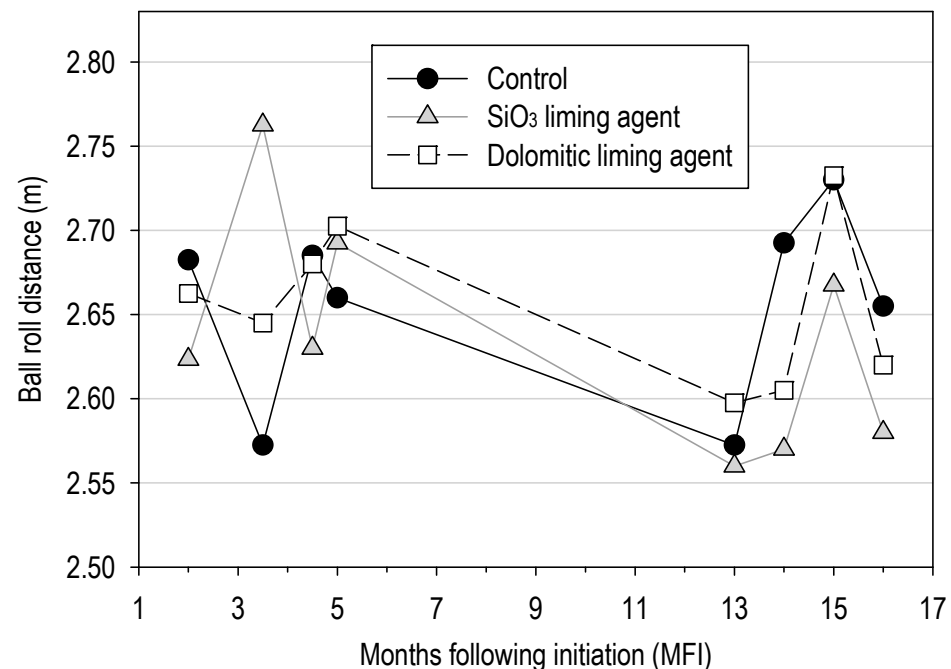
Relative to the alternative,  $\text{SiO}_3$  liming agent treatment significantly increased ( $p < 0.01$ ) mean leaf Si (Table 1). The differences amounted to mean increases of 1.0 and 1.5  $\text{mg g}^{-1}$  relative to dolomitic-liming-agent-treated or untreated plots, respectively. These leaf Si concentrations exceed the  $\text{SiO}_3$ -fertilizer-induced increase reported of either Penncross or Cato:Crenshaw putting greens in North Carolina [9] but are slightly less than the  $\text{SiO}_3$  liming agent-induced increases observed of a Declaration fairway in PA [13].

The range of Penn G2 creeping bentgrass leaf Si increases reported herein is an order of magnitude less than the  $\text{SiO}_3$  liming agent-induced mean increase in clippings of a L93 putting green maintained in Kansas [11]. In the third year of that study, cumulative  $\text{CaSiO}_3$  applications totaling 12.2 or 24.4  $\text{Mg ha}^{-1}$  fostered leaf Si concentrations from 18.1 to 26.7  $\text{mg g}^{-1}$ . These remain the highest creeping bentgrass leaf Si concentrations ever reported in the literature. Given  $\text{H}_4\text{SiO}_4$  solubility relates directly to aqueous pH level, these elevated levels of leaf Si may have resulted from the greater and more frequent  $\text{SiO}_3$  applications, as well as the 7.9 soil pH underlying treated plots of the L93 putting green [11].

Statistically increased ( $p < 0.01$ ) silicon uptake by turfgrass managed on  $\text{SiO}_3$ -liming-agent-treated plots was observed relative to limestone- or untreated plots (Table 1). This increased uptake corresponded to the observed increase in soil extractable silicon, i.e., availability (Figure 2B), yet comprised an infinitesimal fraction of the total Si applied.

### 3.4. Putting Green Speed and Root Length Density

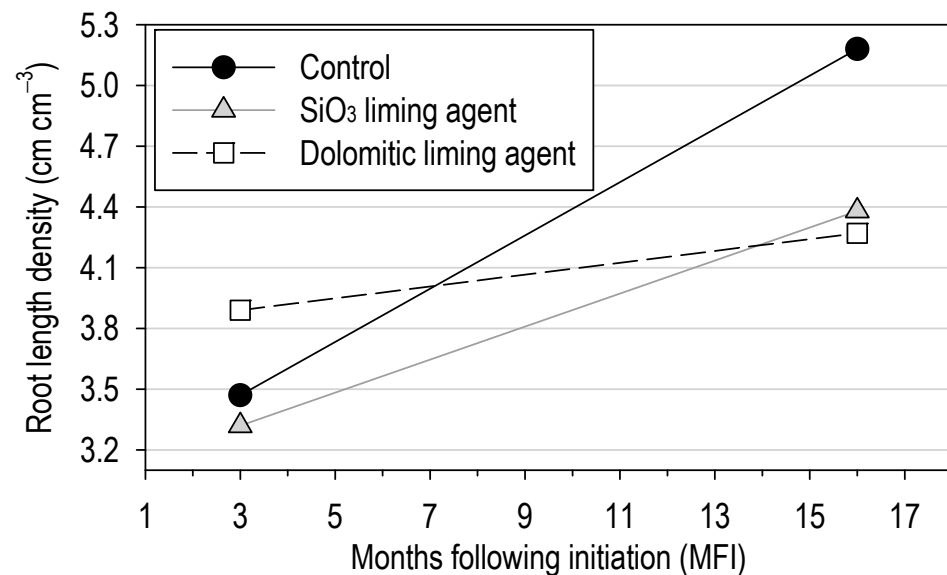
Mean ball roll distance, i.e., putting green speed, varied over the four monthly observations made in each study year (Figure 5) but was not influenced by  $\text{SiO}_3$  and/or liming agent treatment (Table 1). While inconclusive, these results are novel in that they comprise the first report of replicated putting green ball roll distance response to silica treatment.



**Figure 5.** Cohabited putting green ball roll distance by treatment and months following initiation (MFI). Mean values displayed are pooled over four (4) replicates. No significant differences ( $\alpha = 0.05$ ) were observed for liming agent treatment by time.

Root length densities varied significantly by collection date (Figure 6) but were similar to creeping bentgrass root length densities observed in the 7.5 to 15 cm depth of a putting green maintained in Texas [32]. Root length density in the 5 to 15 cm below the surface of

this Penn G2 creeping bentgrass putting green was not significantly influenced by liming agent treatment (Table 1). These results were not unexpected, given optimal creeping bentgrass performance is observed at a soil pH level between 5.5 and 6.5 [33]. However, the data do confirm previous conclusions of field research evaluating foliar silicate treatment of various creeping bentgrass putting greens in North Carolina, where root masses were unaffected by semi-monthly application of 0, 25, or 50 kg Si ha<sup>-1</sup> [9].



**Figure 6.** Cohabited putting green summer root length density in the 5 to 15 cm soil depth by liming agent treatment and months following initiation (MFI). Mean values displayed are pooled over five (5) replicates. No significant differences ( $\alpha = 0.05$ ) were observed for liming agent treatment by time.

#### 4. Conclusions

Relative to untreated plots, the described applications of a silicate-rich, 790 g CaCO<sub>3</sub> equivalent kg<sup>-1</sup> liming agent increased soil extractable Si level throughout the upper 15 cm of putting green rootzone. This described treatment also increased creeping bentgrass clipping mean leaf Si content by 1.0 or 1.5 mg g<sup>-1</sup> relative to dolomitic lime or no treatment, respectively. Yet these gains did not influence creeping bentgrass putting green canopy color, canopy density, ball roll distance, or 5 to 15 cm deep root length density over the 2-year experimental period. While significant differences in clipping yield from untreated and/or liming agent-treated plots were observed at 4 to 17 MFI, no liming agent consistently outperformed the other. Despite exogenous Si treatment having been shown to support the resilience and yield of numerous monocotyledonous species, these and other recent field data indicate creeping bentgrass is not likely one of them. Nevertheless, further research on creeping bentgrass response to silica-rich liming agents is warranted, particularly under suboptimally acidic field conditions.

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