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Evaluating the Effects of Silicon and Nitrogen Fertilization on Wheat Production

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EVALUATING THE EFFECTS OF SILICON AND NITROGEN FERTILIZATION ON WHEAT PRODUCTION

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Abstract

Silicon (Si) fertilization provides numerous benefits to plants which can in turn lead to improved crop yields. Field studies were established at multiple sites in Louisiana on alluvial flood plain soils to establish an optimum application rate for $CaSiO_3$ slag for wheat (*Triticum aestivum)* and determine which parameters contribute to grain yield increases. Treatments were arranged in a randomized complete block design with four replications consisting of twelve treatments: a factorial combination of two N (101 and 145 kg ha^{-1}) and five Si rates (0, 1, 2, 4.5, and 9 Mt ha^{-1} as calcium silicate slag - $CaSiO_3$, 14% Si), and two control plots (with and without lime). Grain yield and yield components were determined. Straw and grain samples were analyzed for Si and essential nutrient content. Soil samples taken at midseason and harvest were analyzed for Mehlich-3 extractable nutrients and Si content by 0.5 M acetic acid extraction procedure. In 2013, higher grain yields were observed at 101 kg N ha^{-1} compared to 145 kg N ha^{-1} with the highest yields seen with 2 Mt ha^{-1} $CaSiO_3$. In 2014, higher yields were achieved at the higher N rate of 145 kg ha^{-1}. Analysis of variance (AOV) at P<0.1 showed effects of N on tiller and panicle number, spike length, and increased weight of 1,000 grains and spikes, and increased grain weight. Silicon effects were observed in spike weight and length, weight of 1,000 grains and the number of grains per spike. Mean separation using Fisher's LSD (P<0.1) showed effects of Si on further yield components such as the number of grains per spike. Data show an increase in some essential nutrients in the soil (e.g. Ca, Mg, S). Nitrogen and Si both influenced the concentration and uptake of nutrients and

certain heavy metals in straw and grain. Increased N application lead to greater leaf rust coverage (*P*<0.01) but significant effects of Si were not observed. Although further research is necessary, the results of this research will help establish the links among Si fertilization rates, level of soil Si and plant essential nutrients, grain yield and its components.

Chapter 1. Introduction

Wheat (*Triticum aestivum*) is one of the most important crops worldwide with global production exceeding that of all other crops (Briggle and Curtis, 1987). It has been reported that people receive more nourishment from wheat than any other food grain (Reitz, 1967). Globally, the United States is one of the largest producers of wheat, ranking third in planted acreage behind corn and soybeans from 2001 to 2010 (USDA-ERS, 2014). In 2013, there was nearly 18.5 million hectares of wheat harvested in the US with a total production value of close to 14.5 billion dollars (USDA-NASS, 2014). Despite these notable statistics, wheat production in the US has been on the decline since the 1980's, in part because of crop competition within the US and a more competitive global market (USDA-ERS, 2014). Wheat is considered a major crop in Louisiana but other crops can often be planted in its place. There were approximately 103,000 ha^{-1} of wheat harvested in LA in 2013 with a total production value around 103 million dollars (USDA-NASS, 2014). Louisiana's subtropical climate and high annual rainfall create further challenges for wheat production. These factors cause increases in pest and disease incidences and development, poor nitrogen (N) utilization, and short grain fill periods (Mascagni et al., 1997). With a substantial amount of research on the use of silicon (Si) in crop production over the past several decades, mostly with rice (*Oryza sativa*) and sugarcane (*Saccharum officinarum*), more research is beginning to focus on wheat.

Silicon is a naturally occurring element in the soil and the second most abundant element in the earth's crust. It is not an essential nutrient for all plants but it is considered a beneficial nutrient for many species (Epstein, 1994). While it is prevalent in the soil, Si primarily exists as silica (SiO_2) which is not available for plant uptake. Silicon must be in the form of mono-silicic acid (H_2SiO_4) to be taken up by plants and the natural dissolution of SiO_2 to H_2SiO_4 in the soil is slow (Raven, 1983). Once Si is taken up by plant roots it is deposited as amorphous silica ($SiO_2 \cdot nH_2O$) or opal phytoliths in cell lumens, cell walls and intercellular spaces (Raven, 1983; Marschner, 1990). Once it is deposited to respective sites within plant tissue, SiO_2 is not redistributed (Epstein, 1994). The structural integrity and rigidity from the deposited SiO_2 is the basis for many of the benefits associated with Si uptake. Several good reviews (Jones and Handreck, 1967; Raven, 1983; Epstein, 1999) on Si and its benefits are available.

Lodging is a common problem among grasses and agronomic crops, especially under high amounts of N fertilizer, resulting in decreased yields (Berry et al., 2000). Increased tissue SiO_2 has been shown to alleviate lodging effects. Leaves become more erect which decreases shading in the lower canopy and allows for greater surface area for sunlight contact, resulting in higher rates of photosynthesis (Epstein 1994).

Perhaps one of the most studied and greatest benefits of Si is its role in reducing effects of abiotic and biotic stresses in plants. Harder plant surfaces make it more difficult for fungal hyphae and insects to penetrate and spread disease (Jones and Handreck, 1967). Decreases in the severity of blast and sheath blight in rice have been observed as well as for powdery mildew in barley (*Hordeum vulgare*), cucumber (*Cucumis sativus)*, melon (*Cucumis melo)* and wheat (Ma et al., 2001). While beneficial effects are not as pronounced under optimum growing conditions they are obvious when plants are under stress (Epstein 1994).

While the critical levels for soil Si are still being developed, Korndorfer et al. (2001) reported a critical level of 19 mg kg^{-1} using 0.5 M acetic acid extraction procedure for Histosol soils of the Florida Everglades. Histosols and other highly weathered, leached or organic soils are commonly deficient of Si (Foy, 1992). Soil H_2SiO_4 levels can be raised with the use of Si fertilizers. Foliar and soil applied forms of Si are currently available today but the most common sources are slag materials. Slags, commonly calcium silicate ($CaSiO_3$) slags, are by-products from the steel industry as well as elemental phosphorus production in electric furnaces and contain varying percentages of Si (Ma and Takahashi, 2002; Alvarez et al., 1988). The use of slags for rice and sugarcane production is a common practice (Epstein, 1994). Slags are used for Si fertilization in numerous countries including Japan, Brazil, and the US (Datnoff et al., 2001). Slags are sometimes needed in high application rates. Korndorfer et al. (2001) reported 4.5 Mt ha^{-1} as a common rate for rice production but responses in yield have been observed at up to 15 Mt ha^{-1}. However, Ma and Takahashi (2002) reported somewhat lower rates of 1.5 to 2 Mt ha^{-1} as common rates for many areas in Japan. Slags are used for their liming potential as well as a Si source and this added benefit can further justify higher application rates. Farmers can supply Si to crops while adjusting soil pH, a necessary and common practice. Nolla et al. (2013) report slags being as effective and sometimes more effective than the common liming material ($CaCO_3$) at correcting soil acidity, noting that slags are almost 7 times more soluble than limestone. Further, acidity can be neutralized deeper in the soil profile because of the greater reactivity of silicates and residual effects have been observed lasting up to 3-5 years.

There has been a wealth of research showing that Si can increase growth parameters and grain yield. Ma et al. (1989) reported increases in the number of panicles, spikelets per panicle, and a remarkable decrease in the number of blank spikelets when Si was applied to rice plants. They did not observe any differences in the weight of 1,000 grains but increases in grain weight were observed by others (Balasta et al., 1989). Abro et al. (2009) conducted a study where silicic acid was applied directly to the soil in a pot experiment in wheat. They reported increases in height of wheat treated with low and moderate Si levels (2.5 and 5.0 g per kg^{-1}, respectively) as well as longer spikes and higher number of grains per spike than untreated wheat plants. Conversely, the application rate of 7.5 g kg^{-1} of silicic acid decreased growth parameters and yield demonstrating the negative effect of over-application of Si.

It is well known that N is the most limiting plant nutrient in non-leguminous crop production systems and therefore it is often applied in large amounts. To prevent deficiencies, producers typically apply N in excess of the crop requirement. Excessive application of N fertilizer may also result from the use of ineffective N decision tools or from not using them at all. Excessive use of N fertilizer in agricultural lands is a non-point source of pollution to surface and ground-water systems (Carpenter et al., 1998). In addition, excessive N application can also result in lodging and increases in pest and disease damage (Berry et al., 2000; Miller et al., 1960; Slaton 2003), eventually reducing yield and income. Because of the well-known role of Si in improving plant mechanical strength and protective layers, the interaction between Si and N fertilizer has been evaluated in crops like rice and sugarcane (Mauad et al., 2003; Meyer and Keeping, 2005). Mauad et al. (2003) reported that N fertilization increased the number of stems and panicles while Si fertilization decreased the number of blank spikelets per panicle. Increases were observed for grain mass but Si did not have an effect on grain productivity. Increases in plant height were seen at lower N rates but were not affected by Si. Work by Meyer and Keeping (2005) shows that Si reduced the susceptibility of sugarcane to the African sugarcane borer, *Eldana saccharina*, under multiple N rates. Interestingly, they concluded that the tissue N/Si ratio was more correlated with resistance to *E. saccharina* than either element on its own. There are other avenues of interest regarding the interactions of N and Si. In 1989, a study by Wallace found that less Si was taken up by plants as the N supply increased. As N fertilizers are an integral part of a crop production system, it is essential to understand the relationship between N and Si.

Many studies have demonstrated the beneficial effects of Si to crops but the combined effects of Si and N is not well known in wheat in areas in the US where disease pressures are high, such as Louisiana. A better understanding of

Si and N nutrition and the development of proper fertilization rates could help meet some of the challenges facing wheat production in the region. This study was conducted to: 1) establish an optimum rate for Si fertilizer for wheat production in Louisiana at sufficient and high N application rates, and 2) evaluate the effects of Si and N on disease indices, nutrient uptake, select agronomic parameters, lodging effects, and yield components of wheat.

Chapter 2. An Investigation on the Effects of Calcium Silicate Slag Applications on Wheat Yield at Sufficient and High Nitrogen Application Rates

2.1 Introduction

Wheat (*Triticum aestivum*) is one of the most important crops worldwide with global production exceeding that of all other crops (Briggle and Curtis, 1987). It has been reported that people receive more nourishment from wheat than any other food grain (Reitz, 1967). The United States is one of the largest global producers of wheat and ranked third in planted acreage during the first 10 years of the 2000's (USDA-ERS, 2014). There were close to 18.5 million hectares of wheat harvested in the US in 2013, valuing close to 14.5 billion dollars (USDA-NASS, 2014). Wheat production in the US can fluctuate but there has been an overall decline in production since the late 1980's. This is partly due to a more competitive global market and partly because of an increase in crop competition within the US (USDA-ERS, 2014). Wheat is a major crop of Louisiana but state production has followed that of the national trend. Farmers will sometimes plant other crops in the place of wheat because they are more profitable. High annual rainfall and the high temperatures are common in Louisiana. The subtropical climate can cause increases in pest and disease problems, poor nitrogen (N) utilization, and short grain fill periods (Mascagni et al., 1997). Silicon (Si) is a beneficial plant nutrient that has been shown to improve yields in a variety of crops, especially members of Poaceae family, by providing a wide range of benefits (Epstein, 1994). Wheat is a Si accumulator, capable of accumulating close to 4% Si in tissue, but is not as readily used in Si research like other crops such as rice (*Oryza sativa)* and sugarcane (*Saccharum officinarum)* (Ma et al., 2001; Rafi et al., 1999).

Silicon is naturally occurring in the soil and is the second most abundant element in the earth's crust. Though Si is essential for some it is not recognized as an essential nutrient for all plants (Epstein, 1994). Silicon is prevalent in the soil but primarily exists as silica (SiO_2) which is not available for plant uptake. Silicon must be taken up by plants in the form of mono-silicic acid (H_2SiO_4) and the natural dissolution of SiO_2 to H_2SiO_4 in the soil is slow (Raven, 1983). Upon uptake by plant roots, Si is deposited as amorphous silica ($SiO_2 \cdot nH_2O$) or opal phytoliths in cell lumens, cell walls and intercellular spaces (Raven, 1983; Marschner, 1990). Once it is deposited SiO_2 is not redistributed with the plant (Epstein, 1994). Strengthening these protective layers and the increase in overall structural integrity is what provides the basis for many of the benefits associated with Si uptake in plants. Silicon has been shown to increase resistance to multiple biotic and abiotic stresses such as lodging, disease, and pest damage (Fallah, 2012; Ma et al., 2001; Meyer and Keeping, 2005). Positive responses of plant growth parameters to Si fertilization have been observed. Ma et al. (1989) reported increases in the number of panicles, spikelets per panicle, and decreases in the number of blank spikelets when Si was applied. Increases in grain weight were also observed, as well as plant height and longer spikes in wheat (Balasta et al., 1989; Abro et al., 2009). These and other benefits of Si fertilization can all contribute to yield increases.

Highly weathered, leached or organic soils such as Histosols are commonly deficient of available Si (Foy, 1992). Soils planted to Si-accumulating crops can also diminish Si levels, furthering the potential responses to Si fertilization (Meyer and Keeping, 2001; Savant et al., 1997). Silicate slags are common sources of Si and are by-products from the steel manufacturing industry as well as from elemental phosphorus production (Ma and Takahashi, 2002; Alvarez et al., 1988). Silicon fertilization has become a common practice contributing to higher yields in crops such as rice and sugarcane (Epstein, 1994). The use of slags is widespread in Japan for degraded paddy soils in rice production (Ma and Takahashi, 2002). Yoshida (1981) reported that yield increases of 10% are common in these and similar areas, and when leaf blast is severe, yield increases by up to 30% were observed. Using silicate slags, Korndorfer et al. (2001) reported yield increases in 19 out of 28 field experiments in rice production in the Everglades Agricultural Area in Florida. In a study conducted by Raid et al. (1992), sugar yield of cane applied with 6.7 Mt ha^{-1} were 17.2 and 21.8% higher than the untreated cane for two successive cropping years. Korndorfer et al. (2001) established 4.5 Mt ha^{-1} as an optimum rate for rice production but responses in yield have been observed at up to 15 Mt ha^{-1}. While higher rates are sometimes needed to reach greater yield increases this is not always the case. Ma and Takahashi (2002) reported somewhat lower rates of 1.5 to 2 Mt ha^{-1} as common for many areas in Japan. Like with other plant nutrients, fertilizer application rates can vary depending on several factors including soil type, type of crop, and existing soil nutrient status.

As N is the most limiting plant nutrient in non-leguminous crop production systems and therefore the most often applied, it is important to understand the interactions of Si with N. To prevent deficiencies, producers typically apply N in excess of the crop requirement. Excessive applications of N fertilizer can also result from not using effective N decision tools. Over-use of N fertilizers in agriculture is a non-point source of pollution to surface and groundwater systems (Carpenter et al., 1998).Excessive N application can also result in lodging and increases in pest and disease damage (Berry et al., 2000; Miller et al., 1960; Slaton 2003), eventually reducing yield and income. The interaction between Si and N fertilizer has been evaluated in crops like rice and sugarcane (Mauad et al., 2003; Meyer and Keeping, 2005). A study of the effects of N and Si nutrition on the susceptibility of sugarcane to the African sugarcane borer (*Eldana saccharina)* by Meyer and Keeping (2005) not only showed that Si reduced the susceptibility to the pest across multiple N rates but that tissue N/Si ratios were more correlated with resistance to *E. saccharina* than N or Si alone. A study by Wallace in 1989 found that as the N supply to monocot species increased, the uptake of Si decreased.

While the benefits of Si in wheat have been documented, the combined effects of N and Si fertilization have not been evaluated in wheat, particularly in Louisiana where disease pressures are high. Implementation of proper management of N and Si fertilizer can alleviate these production challenges in wheat. Currently, there is no existing guideline on Si fertilization for wheat production in Louisiana nor documentations on its impact when combined with sufficient and high N fertilization schemes. Therefore this study was conducted to establish a Si application rate that can maximize wheat grain yield under sufficient and high N application rates.

2.2 Materials and Methods

2.2.1 Site Description, Treatment Structure, and Trial Establishment

This study was conducted from 2012-2014 with a total of three site-years. The first site-year was established in 2012 in St. Joseph (Latitude 31°, 56’, 42.6” N; Longitude 91°, 13’, 34” W), Louisiana on a Commerce silt loam soil (Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts). In 2013, this study was established at two locations:(1) St. Joseph, Louisiana (Latitude 31°, 56’, 41.0” N; Longitude 91°, 13’, 25.8” W) on a field with Sharkey-Tunica-Newellton complex (Very-fine, smectitic, thermic Chromic Epiaquerts) and Commerce silt loam soil types and (2) Ben Hur Research farm (Latitude 30°, 21’, 40.4” N; Longitude 91°, 10’, 01.9” W) near Louisiana State University campus in Baton Rouge on a Cancienne silt loam soil (Fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquepts). All of these soils are found on the alluvial plain along the Mississippi River.

All three site-years were established using a dryland, conventional tillage system. Table 2.1 provides dates of major field activities and plot sizes used for the three site-years.

Table 2.1. Record of trial establishment and field activities.

Location	Year Est.	Site-Year ID	Plot Size, m	Date					
				Si Application	Planting	N Application	Feekes 5 (BM1)	Feekes 10.5 (BM2)	Harvest
St. Joseph	2012	NERS 2013	1.5 x 5.2	9-Nov-12	9-Nov-12	1-Feb-13	14-Mar-13	17-Apr-13	7-Jun-13
St. Joseph	2013	NERS 2014	1.5 x 3.7 [1]	14-Nov-13	16-Nov-13	21-Feb-14	5-April-14 [2]	16-Apr-14	6-Jun-14
Ben Hur	2013	BH 2014	1.2 x 4.6	8-Nov-13	11-Nov-13	22-Feb-14	21-Mar-14	10-Apr-14	22-May-14

[1] plot sizes varied from 3.4 - 4.3 m

[2] BM1 was Feekes GS 9 for NERS 2014

Initial soil data for all three site-years is summarized in Appendix A in Table A.1. The treatment structure was a two-way factorial (two N rates x five $CaSiO_3$ slag rates) in a randomized complete block design with four replications. Each replication consisted of two checks (no N and Si applied), without lime and with lime at 4.5 MT ha^{-1} (Table 2.2). The lime treatment was incorporated into the treatment structure to differentiate treatment effects from a pH effect since slags increase soil pH. Two N rates of 101 and 145 kg ha^{-1} were used for this study using urea (46% N) as the N source. The 101 kg N ha^{-1} rate is the standard rate for wheat production in LA and the 145 kg N ha^{-1} rate is considered an excessive rate, a rate sometimes used by farmers in the state. For each N rate, there were five $CaSiO_3$ slag (Plant Tuff®) rates of 0, 1, 2, 4.5, and 9 Mt ha^{-1} which were equivalent to 0, 120, 240, 540, and 1080 kg Si ha^{-1}, respectively. Phosphorus (P) and potassium (K) fertilizer were applied to fields when necessary according to the test results and recommendations of the LSU AgCenter Soil Testing and Plant Analysis Laboratory to ensure neither nutrient was limiting in the soil. Calcium silicate slag is the form of Si used for this study. It is a byproduct from steel industries containing 14% Si. Other known components of the slag material used can be found in Appendix A in Table A.2. Slag and lime amendments are similar in their physical properties and method of application. Slag and lime treatments were weighed into plastic bags and then broadcast applied by hand to individual plots in November of each year. Treatments were then incorporated into the soil to a depth of about 7.5 cm.

Winter wheat variety Terral 8525 was drill seeded at the rate of 101 kg ha^{-1} for NERS 2013 and 2014 and 113 kg ha^{-1} for BH 2014 within a week of slag and lime applications.

Table 2.2. Treatment structure and descriptions.

Treatment Number	N rate, kg ha^{-1}	$CaSiO_3$ slag, Mt ha^{-1}
1	0	0
2	0	0 + 4.5 Mt ha^{-1} lime
3	101	0
4	101	1
5	101	2
6	101	4.5
7	101	9
8	145	0
9	145	1
10	145	2
11	145	4.5
12	145	9

The two N treatments were applied around Feekes growth stage (GS) 4 (Large, 1954). Urea was weighed into plastic bags and then broadcast applied by hand to the corresponding plot assignment. Recommended weed management practices from the LSU AgCenter were followed.

2.2.2 Soil Sampling

Soil samples were taken at two sampling times during the growing season: midseason around Feekes 10.5 (April) and at harvest (June). Each sample consisted of twelve soil cores from a depth of about 15 cm where six cores taken from two inner rows, adjacent to where biomass samples were cut.

Soil samples were oven-dried (Despatch LBB series; model number LBB2-18-1) at 55°C for about 4-5 days and then ground using a Humboldt soil grinder and passed through a 2 mm sieve for later analysis.

Laboratory Analysis

2.2.3 Soil Analysis

2.2.3.a. Extractable Silicon. Ten (10) mL of 0.5 M acetic acid was added to 1 g soil samples and placed on a reciprocal shaker (Eberbach; model number E6010.00) for 1 hour. Immediately after shaking, samples were filtered with Whatman No. 1 filter paper into 50 mL centrifuge tubes (Korndorfer et al., 1999). Plant-available Si was determined by a modified Molybdenum Blue Colorimetry (MBC) procedure as outlined by Korndorfer et al. (2001). A 0.5 mL aliquot was pipetted into 50 mL centrifuge tubes. Ten mL of DI water was added followed by 0.5 mL of 1:1 HCl:DI water solution. One (1) mL of 10% ammonium molybdate ($\{NH_4\}_6Mo_7O_{24}\cdot 4H_2O$) was added and samples were left to sit for 5 minutes. After 5 minutes, 1 mL of 20% tartaric acid was added to tubes and they were gently swirled by hand for 10 seconds and then left to sit for 2 minutes. One (1) mL of the reducing agent, ANSA, (0.5 mg 1-amino-2-naphthol-4-sulphonic acid + 1.0 g sodium sulfite + 30.0 g sodium bisulfite in DI water with a final volume of 250 mL) was added. Finally, DI water was added to bring the samples up to a final volume of 25 mL and tubes were capped and then shaken very well. After 5 minutes the absorbance reading was measured using a Hach DR 5000 spectrophotometer at 630 nm.

2.2.3.b. Extractable Nutrients by Mehlich-3 Procedure (Mehlich, 1984). A 2 g soil sample was weighed out into 100 mL plastic bottles followed by the addition of 20 mL of Mehlich-3 solution (dilute acid-fluoride-EDTA solution, pH 2.5). The samples were shaken on a reciprocal shaker set at high speed for 5 minutes and then filtered using Whatman No. 42 filter paper. The extract was then analyzed using Inductively Couple Plasma (ICP) – Optical Emission Spectroscopy (OEM) for several essential nutrients as well as some heavy metals (Spectro Ciros CCD ICP analyzer).

2.2.3.c. Inorganic Nitrogen. Five (5) grams of soil was added with 35 mL of 1 M KCl, shaken for 1 hour on a reciprocal shaker at high speed, and filtered with Whatman No. 42 filter paper. Sample extracts were analyzed for nitrate (NO_3^-) and ammonium (NH_4^+) content by spectrophotometric measurement using an automated flow injection system (Lachat QuickChem 8500 series 2). Nitrate and ammonium were measured simultaneously from the same extract utilizing the multiple channels on the Lachat machine. Nitrate was determined using a modification of the method outlined by Keeney and Nelson (1982) where nitrate is converted to nitrite while passing through a cadmium column and then reacting with the coloring reagent sulfanilamide, and measured at 520 nm. Ammonium was measured at 660 nm after a reaction with the salicylate-nitroprusside coloring reagent (Keeney and Nelson, 1982).

2.2.3.d. Soil pH (1:1 method). The pH of soil was measured using a 1:1 soil to DI water ratio. Five (5) grams of soil weighed into 50 mL centrifuge tubes was added with 5 mL DI water. Tubes were shaken on a reciprocal shaker for 1 hour and the pH was measured using an Oakton pH 5+ digital pH meter.

2.2.3.e. Total Soil Nitrogen. Total N was determined using a dry combustion method where 20 mg of soil was weighed into tin capsules and measured with a C:N analyzer (Elementar Americas Inc, Vario EL Cube).

2.2.4 Grain Yield.

Plots from NERS 2013 and 2014 were harvested with a Massey Ferguson 8XP and a Wintersteigher Classic plot harvester was used for BH 2014. Grain subsamples collected from each site during harvesting were weighed and then analyzed for moisture content and test weight using a grain analysis computer (model number GAC2500 AGRI). Grain moisture content was adjusted to 12% and yield calculated in bushels per acre using the formula below:

$$\text{Grain Yield (bu/ac)} = \frac{\left[\dfrac{\text{grain weight (lbs/plot)}}{\text{plot size (ft}^2\text{)}} \times \dfrac{43{,}560\ \text{ft}^2}{\text{ac}}\right]\left[\dfrac{100\text{-Moisture Content}}{88}\right]}{\text{Test Weight}}$$

Grain yield in bushels per acre was then converted to kg ha^{-1} using the formula:

$$\text{Grain Yield (kg ha}^{-1}\text{)} = \left[\frac{\text{Yield, bu}}{\text{ac}}\right] \times \frac{60\text{ lbs}}{\text{bu}} \times \frac{1\text{ kg}}{2.2\text{ lbs}} \times \frac{2.47\text{ ac}}{\text{ha}}$$

2.2.5 Data Analysis

Analysis of variance was performed using PROC MIXED in SAS 9.3 to determine significant main effects of N, Si, and N x Si interactions on measured parameters (SAS, 2012). The fixed effects were N, Si, and their interaction while replications were considered a random effect. Treatments 1 and 2 were deleted and the program was run as a complete factorial in order to determine significant differences in Si treatments at each N rate. Difference of least square means (LSD) was then used to identify treatment differences.

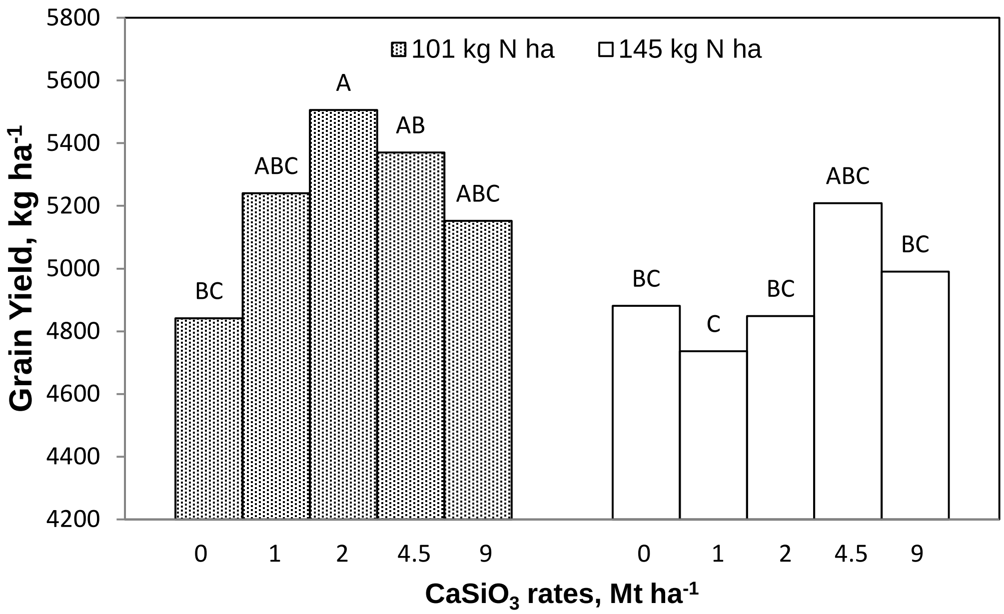
2.3 Results and Discussion

2.3.1 Effects of Varying Si and N Fertilization Rates on Grain Yield

The main effects of N, Si, and N x Si interaction effects on grain yield for all three site-years are reported in Table 2.3. Nitrogen had a significant effect on grain yield in all three site-years while Si effect was only observed in BH 2014. There was no significant interaction effect detected between N and Si on grain yield. A mean separation procedure (LSD, $P<0.1$) was performed in SAS to determine significant differences within N rates and these results can be seen in Figures 2.1 and 2.2. Higher yields were observed at the lower N rate of 101 kg ha^{-1} compared to 145 kg ha^{-1} ($P<0.1$) in NERS 2013 (Figure 2.1). This differed from both sites for 2014 (Figure 2.2) in that higher yields were seen at the higher N rate of 145 kg ha^{-1} (P<0.01). The NO_3^- levels in midseason soil samples were higher for NERS 2013 than the other two sites if the 0 Si treatments for each N rate are considered (Appendix C). There was also a lot of rain around the time of N application and some of the N applied could have leached. These factors could partly explain the greater grain yield response to N observed for NERS 2014 and BH 2014. For NERS 2013, the highest yields were observed with the combination of 101 kg N ha^{-1} and 2 Mt ha^{-1} of $CaSiO_3$, a 13.7% increase in yield from the 0 Si treatment of the same N rate (P<0.1). The highest yield at the 145 kg ha^{-1} N rate was achieved in combination with 4.5 Mt $CaSiO_3$ ha^{-1}, but this treatment was not significantly different than the 0 Si rate at the same N level. No significant differences were observed among Si rates for grain yield for NERS 2014. For BH 2014, there was a significant main effect of Si on yield. Higher yields were observed at the highest Si rate of 9 Mt ha^{-1} for both N rates (P<0.1).

Table 2.3. Analysis of variance on grain yield for all site-years.

Analysis of Variance		Grain Yield, kg ha^{-1} NERS 2013	NERS 2014	BH 2014
N effect	*P*-value	<0.1	<0.001	<0.001
Si effect	*P*-value	NS	NS	<0.1
N x Si Interaction	*P*-value	NS	NS	NS



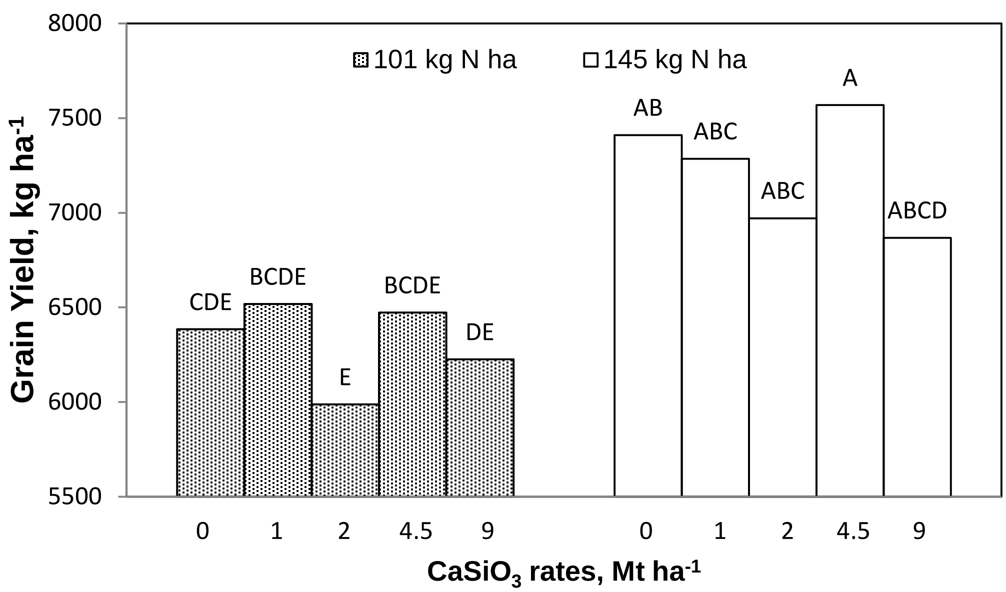


Figure 2.1. Grain yield of wheat applied with varying rates of $CaSiO_3$ slag under sufficient and high N application rates, NERS 2013 (above) and NERS 2014 (below). [1]Differences in letter groups are results of mean separation using LSD in SAS.

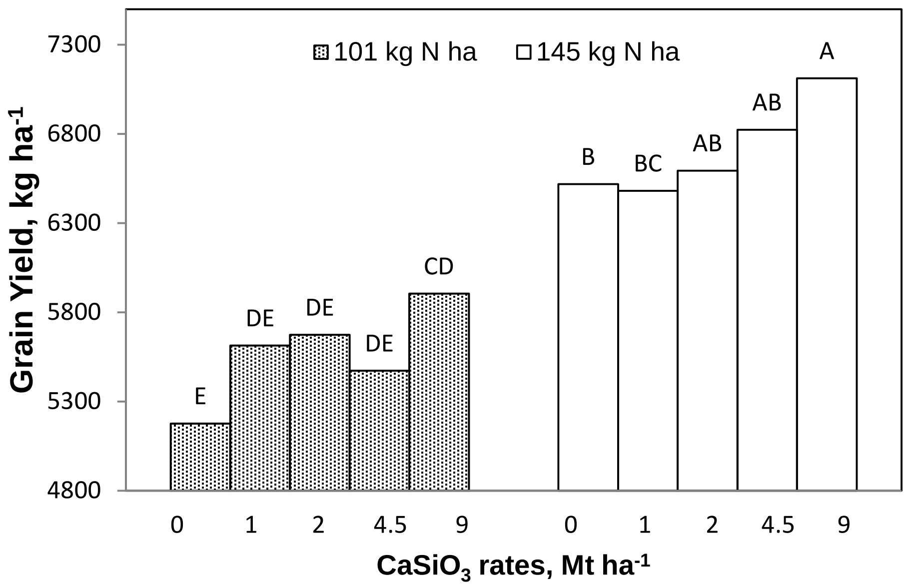


Figure 2.2. Grain yield of wheat applied with varying rates of $CaSiO_3$ slag under sufficient and high N application rates, BH 2014. [1]Differences in letter groups are results of mean separation using LSD in SAS.

Results for NERS 2013 and BH 2014 agree with the findings of many others that Si fertilization can improve grain yields. Korndorfer et al. (2001) reported yield increases in rice in several different field experiments. Yield increases have also been reported by Yoshida (1981) for rice production in Japan. In wheat, Abro et al. (2009) and Tahir et al. (2006) both reported increases in yield. It is difficult to assess an application rate for $CaSiO_3$ slag based solely on these results as these findings will be better suited for decision making alongside replicated studies. Though it was the highest yielding rate for both N rates in BH 2014, an application rate of 9 Mt ha^{-1} of slag is not a practical recommendation. Slag materials are by-products and relatively inexpensive compared to other common fertilizers but transportation costs are expensive. The amount of yield increases seen in BH 2014 would likely not justify the cost of applying 9 Mt $CaSiO_3$ ha^{-1}. A Si rate of 2 Mt ha^{-1}, on the other hand, could be of economic benefit to producers based off yield increases of 13.7% which were observed in one site year of this study. However, a detailed cost benefit analysis would need to be performed and this Si rate of 2 Mt ha^{-1} was only shown to provide significant yield increases in one out of three sites.

2.3.2 Effects of Varying Si and N Fertilization Rates on pH, Extractable Si, Essential Nutrients, and Heavy Metals in Soil Samples

The pH, 0.5 M acetic acid extractable Si, soil NO_3^- and NH_4^+, and Mehlich-3-extractable nutrients and heavy metals of soil sampled at harvest are summarized in Tables 2.4 – 2.9 for each respective site-year. Calcium silicate slag was effective at increasing soil Si and pH for all three site-years. The composition of the $CaSiO_3$ slag material used can be found in Appendix A (Table A.2). As a by-product it contains other elements and the known elements are Ca, magnesium (Mg), Si, manganese (Mn), aluminum (Al), iron (Fe), and sulfur (S). Silicon rates significantly increased the amount of Ca (P<0.01) and Mg (P<0.1) in the soil but this was to be expected because slag material used contains these elements in similar amounts as calcium carbonate (lime treatment). Significant increases in S were observed in harvest soil samples for NERS 2013 and BH 2014 (P<0.05) with increasing $CaSiO_3$. While zinc (Zn) is not expressed as a component of the slag material according to the manufacturer, its availability increased as Si rates increased for all three site years (P<0.05). These results contradict what was expected, as Zn availability decreases with increasing soil pH (Havlin et al., 2005). However, Zn availability still increased despite the rise in soil pH observed as Si rates increased. These results disagree with those by Saleh et al. (2013) and Cunha et al. (2008) where Si applications lead to decreases in extractable Zn. Zinc was not included in the elemental analysis the slag material so it is not known whether it is present or not. However, it is suspected that trace amounts of Zn exist in the composition of the slag which would explain the increases observed in soil samples. Aluminum showed a significant increase in the soil with increasing Si for BH 2014 (P<0.05) but not for the other two sites. Application of $CaSiO_3$ slag affected the amount of chromium (Cr) in the soil as well, increasing availability by about 0.15 mg kg^{-1} between 0 Si and 9 Mt ha^{-1} applied (P<0.01). While Cr is a heavy metal that can have harmful implications to plants and humans at high amounts, 40-70 mg kg^{-1} are reported as average, naturally occurring values in soils by Gonnelli and Renella (2013). Furthermore, the toxicity threshold for plants is described to be 75-100 mg kg^{-1}. The highest average Cr values observed at the highest Si treatment still remained less than 1 mg kg^{-1}. Cadmium levels increased with higher N applied in NERS 2013 (P<0.1) but these levels were not significantly higher than the control treatments where no N or Si were applied. Also, like Cr, values did not reach greater than 1 mg kg^{-1}, falling within the limits (0.1 – 1.0 mg kg^{-1}) of non-contaminated soils (Smolders and Mertens, 2013). Silicon treatments did not affect harvest soil NH_4^+ for any site but there were significant effects of Si on soil NO_3^-. Nitrate levels increased with increasing Si for all three site years. Effects of N and Si on arsenic (As), molybdenum (Mo), sodium (Na), and boron (B) were also evaluated but results are not shown because no values were significant.

Table 2.4. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH, 0.5 m acetic acid extractable-Si, soil NH_4^+ and NO_3^-, and Mehlich-3 extractable macronutrients, NERS 2013, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Silicon and Macronutrients, mg kg^{-1}							
			Si	NH_4	NO_3	P	K	Ca	Mg	S
0	0	5.6	68	9.9	2.6	38	293	2002	494	8
0	0+lime	6.4	87	9.9	3.6	34	280	2359	515	9
101	0	5.7	62	9.8	2.9	31	268	1968	492	8
	1	5.7	60	9.6	3.5	33	284	2079	516	8
	2	6	83	9.8	3.3	31	260	2124	516	8
	4.5	6.3	118	10.2	4.8	35	294	2472	568	10
	9	6.5	138	10.5	4.9	37	266	2447	552	12
145	0	5.4	58	9.7	3.3	35	278	1987	479	8
	1	5.6	64	10.2	4.3	39	280	2070	494	9
	2	6	78	9.0	4.1	35	279	2242	542	9
	4.5	6.2	118	10.0	4.7	38	293	2343	537	9
	9	7	144	10.5	7.6	36	282	2645	592	11
Analysis of Variance										
N Effect	*P*-value	NS	NS	NS	<0.05	<0.1	NS	NS	NS	NS
Si Effect	*P*-value	<0.001	<0.001	NS	<0.001	NS	NS	<0.001	<0.001	<0.01
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 2.5. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH and Mehlich-3 extractable micronutrients and metals, NERS 2013, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Micronutrients and Metals, mg kg^{-1}									
			Cu	Fe	Mn	Ni	Zn	Al	Cr	Pb	Cd	Co
0	0	5.6	2.33	376	127	2.9	2.8	686	0.06	2.3	0.20	1.3
0	0+lime	6.4	2.27	316	123	2.5	2.9	580	0.06	2.2	0.18	1.3
101	0	5.7	2.21	336	128	2.8	2.7	621	0.06	2.1	0.18	1.3
	1	5.7	2.31	354	127	2.7	2.7	663	0.08	2.2	0.19	1.3
	2	6	2.29	334	126	2.6	3.0	636	0.11	2.2	0.18	1.2
	4.5	6.3	2.49	331	119	2.6	3.4	689	0.18	2.2	0.19	1.2
	9	6.5	2.36	345	117	2.5	3.2	690	0.2	2.2	0.17	1.2
145	0	5.4	2.36	389	116	2.8	2.9	698	0.07	2.2	0.19	1.2
	1	5.6	2.3	375	122	2.9	3.0	677	0.09	2.2	0.20	1.2
	2	6	2.46	351	126	2.8	3.2	690	0.13	2.3	0.19	1.3
	4.5	6.2	2.43	350	127	2.8	3.1	704	0.18	2.2	0.19	1.3
	9	7	2.51	315	121	2.6	3.1	690	0.22	2.2	0.19	1.2
Analysis of Variance												
N Effect	*P*-value	NS	NS	<0.1	NS	NS	NS	<0.05	NS	NS	<0.1	NS
Si Effect	*P*-value	<0.001	NS	<0.1	NS	NS	<0.05	NS	<0.001	NS	NS	<0.05
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 2.6. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH, 0.5 m acetic acid extractable-Si, soil NH_4^+ and NO_3^-, and Mehlich-3 extractable macronutrients, NERS 2014, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Silicon and Macronutrients, mg kg^{-1}							
			Si	NH_4	NO_3	P	K	Ca	Mg	S
0	0	5.1	36	15.3	1.3	62	356	2422	603	9
0	0+lime	5.7	62	14.2	2.2	63	367	3107	668	9
101	0	4.9	39	15.5	2.8	64	383	2616	630	9
	1	5.0	51	14.2	2.0	59	337	2493	614	11
	2	5.2	60	14.7	3.0	55	347	2774	661	9
	4.5	5.1	58	15	3.7	66	373	2854	666	10
	9	5.4	93	15.2	3.9	69	378	3132	710	12
145	0	4.8	40	14.3	2.1	56	328	2511	609	9
	1	4.9	49	15.4	3.6	54	327	2576	632	10
	2	4.9	52	15.7	3.6	62	341	2675	636	10
	4.5	5.0	60	16.8	4.7	71	372	2751	651	12
	9	5.5	82	14.7	3.8	59	331	2988	688	11
Analysis of Variance										
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.01	<0.001	NS	<0.05	NS	NS	<0.01	<0.1	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 2.7. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH and Mehlich-3 extractable micronutrients and metals, NERS 2014, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Micronutrients and Metals, mg kg^{-1}							
			Cu	Fe	Mn	Ni	Zn	Se	Al	Pb
0	0	5.1	3.4	542	128	5.1	3.4	0.2	831	3.4
0	0+lime	5.7	3.8	514	108	4.9	3.9	0.3	811	3.5
101	0	4.9	3.6	552	113	5.1	3.6	0.3	848	3.7
	1	5.0	3.5	535	133	5.2	3.6	0.3	828	3.6
	2	5.2	3.8	505	116	4.9	3.8	0.3	798	3.5
	4.5	5.1	3.7	530	109	4.9	4.0	0.2	860	3.6
	9	5.4	3.9	530	107	4.7	4.6	0.3	887	3.6
145	0	4.8	3.6	528	119	5.2	3.3	0.3	844	3.5
	1	4.9	3.6	512	121	5.0	3.4	0.3	831	3.5
	2	4.9	3.6	530	115	5.0	3.6	0.3	853	3.5
	4.5	5.0	3.6	524	109	5.0	4.0	0.2	861	3.6
	9	5.5	3.7	501	111	4.5	4.1	0.2	865	3.5
Analysis of Variance										
N Effect	*P*-value	NS	NS	NS	NS	<0.01	NS	NS	NS	NS
Si Effect	*P*-value	<0.01	NS	NS	NS	NS	<0.01	<0.1	NS	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]Chromium was only analyzed for 2014 sites.

Table 2.8. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH, 0.5 M acetic acid extractable-Si, soil NH_4+ and NO_3-, and Mehlich-3 extractable macronutrients, BH 2014, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Silicon and Macronutrients, mg kg^{-1}							
			Si	NH_4	NO_3	P	K	Ca	Mg	S
0	0	5.6	17	8	1.0	73	171	1713	306	7
0	0+lime	6.1	35	6	1.8	79	173	2043	333	7
	0	5.6	29	7	0.6	70	155	1743	306	5
	1	5.9	27	6	1.0	68	153	1856	322	6
101	2	5.9	30	7	1.0	66	146	1864	328	6
	4.5	6.2	38	7	1.1	72	151	1980	348	7
	9	6.5	56	7	1.3	73	147	2254	383	9
	0	5.6	30	7	0.8	69	151	1771	308	5
	1	5.9	27	7	0.9	66	156	1909	323	6
145	2	5.8	30	7	1.2	69	153	1862	335	6
	4.5	5.9	45	7	1.3	69	155	2082	357	8
	9	6.5	95	8	1.8	72	153	2215	385	9
Analysis of Variance										
N Effect	*P*-value	NS	<0.1	<0.1	<0.05	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.01	<0.001	NS	<0.01	NS	NS	<0.001	<0.001	<0.001
N x Si Effect	*P*-value	NS	<0.1	NS	NS	NS	NS	NS	NS	NS

Table 2.9. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH and Mehlich-3 extractable micronutrients and metals, BH 2014, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Micro-Nutrients and Metals, mg kg^{-1} Cu	Fe	Mn	Ni	Zn	Se	Al	Pb
0	0	5.6	1.8	515	54	2.0	1.7	0.2	673	3.7
0	0+lime	6.1	1.9	499	57	2.0	1.4	0.2	636	3.9
101	0	5.6	1.9	529	64	2.1	1.4	0.2	649	3.8
	1	5.9	1.9	502	63	2.3	1.5	0.2	657	3.9
	2	5.9	1.8	496	65	2.0	1.5	0.2	661	3.2
	4.5	6.2	1.9	511	68	2.2	1.8	0.2	671	3.9
	9	6.5	1.9	505	72	2.0	2.0	0.2	719	4.0
145	0	5.6	1.8	519	63	2.1	1.5	0.2	707	3.6
	1	5.9	2.0	465	64	2.0	1.8	0.2	604	3.8
	2	5.8	1.8	528	70	2.1	1.5	0.2	701	3.7
	4.5	5.9	2.0	500	67	2.2	2.0	0.2	697	3.9
	9	6.5	2.0	503	74	2.1	2.1	0.2	712	3.7
Analysis of Variance										
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.01	<0.1	NS	<0.01	NS	<0.0001	NS	<0.05	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]Chromium was only analyzed for 2014 sites.

Midseason soil samples were also taken at Feekes 10.5 growth stage and results are summarized in Appendix B in Tables B.1 - B.5. Only trends that differ from harvest soil samples will be discussed for midseason samples. Silicon fertilization increased the availability of Al (P<0.01) and Pb (P<0.1) for NERS 2013. A significant N x Si interaction effect was also observed for Pb in this site where the Si rate of 2 Mt ha^{-1} combined with 145 kg N ha^{-1} increased Pb availability as opposed to 101 kg ha^{-1} N at the same Si rate. Naturally occurring in soils, the mean level of Pb in soils is 17 mg kg^{-1} (Steinnes, 2013). By this standard, mean values of < 5 mg kg^{-1} of Pb in soil samples were not alarming. These effects on extractable Pb were no longer significant in harvest soil samples. An increase in available Cu was observed for NERS 2013 and BH 2014 (P<0.01). Nitrogen x Si interactions were also observed for nickel (Ni) in NERS 2013 (P<0.1) and B in NERS 2014 (P<0.05).

2.4 Conclusions

Calcium silicate slag was found to be effective at increasing wheat grain yields at sufficient and high N fertilization rates. While increasing numerical trends were observed for all Si treatment levels when compared to control treatments, significant increases were observed for 2 and 9 Mt ha^{-1} Si rates. The 9 Mt ha^{-1} Si rate is not considered a practical recommendation because material transportation and application costs would likely be too high to provide economic returns. The rate of 2 Mt ha^{-1} is the lowest rate of applied $CaSiO_3$ slag where significant yield increases were achieved. This would be a more practical rate comparable to those of 1.5 - 4.5 Mt ha^{-1} reported as common for rice production

(Ma and Takahashi, 2002; Kordorfer et al., 2001). However, as the 2 Mt ha^{-1} Si rate was only shown to significantly increase grain yields in one out of three site years, more research would need to be conducted to validate an application rate. The inconsistencies observed in responses to Si treatments could be due to varying soil properties. Initial soil Si levels are one such property. NERS 2013 initial soil Si levels were higher than both sites in 2014 and higher soil Si levels were reached. Soil type could have also been a factor that contributed to inconsistent results in responses to Si treatments as NERS 2014 was a heavier textured soil than the other two site years. Nitrogen also affected grain yield with overall increases observed at both N application rates for different site years. Nitrogen and Si both had effects on the availability of certain essential nutrients and heavy metals. Silicon applications showed effects on extractable Ca, Mg, S, Fe, Zn, Mn, Se, NH_4^+, NO_3^-, and Si. Increases in Co, Cr, and Pb were also observed with increasing Si but mean values did not reach contaminated soil levels. Calcium silicate slag is a byproduct and contains some of the elements that were analyzed, explaining some of the increases in availability. Initial soil S levels were below the critical level of 10 mg kg^{-1} (Tables 2.4-2.9) but the magnitude of increase in soil S with increasing slag rates was likely not substantial enough to lead to significant yield increases (Saha, 2008). Although the other nutrients present in the slag were not found limiting in the soil, it is possible that the increased availability of other nutrients, whether direct effects from slag composition or indirect effects from interactions and pH, could have contributed to increases in grain yields. The applications of $CaSiO_3$ slag increased the 0.5 M acetic acid extractable Si and soil pH.

As soil dynamics are very complex and there are numerous sources of variability within field experiments, more research will need to be conducted to further calibrate application rates for $CaSiO_3$ slag for use in wheat production. Because of the effectiveness of $CaSiO_3$ at increasing soil Si and soil pH, it could prove even more beneficial if used as a lime treatment in place of traditional $CaCO_3$. The Si rate of 2 Mt ha^{-1}, in which yield increases of 13.7% were observed for NERS 2013, is comparable to common lime rates.

2.5 References

Abro, S.A., R. Qureshi, F.M. Soomro, A.A. Mirbahar, and G.S. Jakhar. 2009. Effects of silicon levels on growth and yield of wheat in silty loam soil. Pakistan Journal of Botany. 41:1985-1390.

Alvarez, J., G.H. Snyder, D.L. Anderson, and D.B. Jones. 1988. Economics of calcium silicate slag application in a rice-sugarcane rotation in the everglades. Agricultural Systems. 28:179-188.

Balasta, M.L.F.C., C.M. Perez, B.O. Juliano, C.P. Villareal, J.N.A. Lott, and D.B. Roxas. 1989. Effects of silica level on some properties of *Oryza sativa* straw and hull. Canadian Journal of Botany. 67:2356-2363.

Berry, P.M., J.M. Griffin, R. Sylvester-Bradley, R.K. Scott, J.H Spink, C.J. Baker, and R.W. Clare. 2000. Controlling plant form through husbandry to minimize lodging in wheat. Field Crops Research. 67:59-81.

Briggle, L.W. and B.C. Curtis. 1987. Wheat worldwide. *In E.G. Heyne (ed.)* Wheat and wheat improvement. Soil Science Society of America, American Society of Agronomy, Madison USA. 13:1-32.

Cunha, K., C. Nascimento, and A.J. Silva. 2008. Silicon alleviates the toxicity of cadmium and zinc for maize (*Zea mays* L.) grown on a contaminated soil. Journal of Plant Nutrition and Soil Science.171:849-853.

Datnoff, L. E., G. H. Snyder, and G.H. Kornodörfer (ed). 2001. Silicon in agriculture. Studies in Plant Science 8. Elsevier, Amsterdam.

Epstein, E. 1994. The anomaly of silicon in plant biology. Proceedings of the National Academy of Sciences. 91:11-17.

Epstein, E. 1999. Silicon. Annual Review of Plant Physiology and Plant Molecular Biology. 50:641-664.

Fallah, A. 2012. Silicon effect on lodging parameters of rice plants under hydroponic culture. International Journal of AgriScience. 2(7):630-364.

Foy, C. D. 1992. Soil chemical factors limiting plant root growth. Advances in Soil Science. 19:97-149.

Gonnelli, C. and G. Renella. 2013. Chromium and nickel. *In* B.J. Alloway (ed). Heavy Metals in Soils. Environmental Pollution 22. 3rd ed. Springer. 313-333.

Hallmark, C. T., L. P. Wilding, and N.E. Smeck. 1982. Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. 15:263-274.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil fertility and fertilizers: An introduction to nutrient management. Pearson Prentice Hall. 7th ed.

Jones, J.B., B. Wolf, and H.A. Mills. 1991. Plant Analysis Handbook. Micro-Macro Publishing. 23-26.

Jones, L.H.P. and Handreck, K.A.1967. Silica in soils, plants, and animals. Advances in Agronomy. 19:107-149.

Keeney D. R. and D.W. Nelson. 1982. Nitrogen-Inorganic forms. Methods of Soil Analysis, part 2. 9:643-698.

Korndörfer, G. H., G.H. Snyder, M. Ulloa, G. Powell, and L.E. Datnoff. 2001. Calibration of soil and plant silicon analysis for rice production. Journal of Plant Nutrition. 24:7, 1071 – 1084.

Korndorfer, G. H., N. M. Coelho, G. H. Snyder, and C. T. Mizutani. 1999. Avaliacao de metodos de extracao de silicio em solos cultivados com arroz de sequeiro. Revista Brasileira de Ciencia do Solo. 23:101-106.

Kraska, J.E., and G.A Breitenbeck. 2010. Simple robust method for quantifying silicon in plant tissue. Communications in Soil Science and Plant Analysis. 41:2075-2085.

Large, E.C. 1954. Growth stages in cereals: Illustration of Feekes scale. Plant Pathology. 3:128-129.

Ma, J.F., and E. Takahashi. 2002. Soil, fertilizer, and plant silicon research in Japan. Elsevier, Amsterdam.

Ma, J.F., K. Nishimura, and E. Takahashi. 1989. Effect of silicon on the growth of rice plant at different growth stages. Soil Science and Plant Nutrition. 35:347-356.

Ma, J.F., Y. Miyake, and E. Takahashi. 2001. Silicon as a beneficial element for crop plants. *In* Datnoff, Snyder and Kornodörfer (ed.). Silicon in agriculture. Studies in Plant Science 8. Elsevier, Amsterdam.

Marschner, H., Oberle, H., Cakmak, I., and Romheld, V. 1990. Growth enhancement by silicon in cucumber plants *(Cucumis sativus)* depends on imbalance on phosphorus and zinc supply. Plant and Soil. 124:211-219.

Mascagni, H.J. Jr., S. A. Harrison, J. S. Russin, H. M. Desta, P. D. Colyer, R.J. Habetz, W. B. Hallmark, S. H. Moore, J. L. Rabb, R. L. Hutchinson & D. J. Boquet 1997. Nitrogen and fungicide effects on winter wheat produced in the Louisiana Gulf Coast region. Journal of Plant Nutrition. 20:10, 1375-1390.

Mauad, M., C.A.C. Crusciol, H.G. Filho, and J.C. Correa. 2003. Nitrogen and silicon fertilization of upland rice. Scientia Agricola. 60:761-765.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Communications in Soil Science and Plant Analysis. 15:1409-1416.

Meyer, J.H. and M.G. Keeping. 2005. The impact of nitrogen and silicon nutrition on the resistance of sugarcane varieties to *Eldana saccharina* (Lepidoptera: Pyralidae). Proceedings of the South African Sugar Technologists' Association. 79:363-367.

Meyer, J.H., and M.G. Keeping. 2001. Past, present and future research of the role of silicon for sugarcane in southern Africa. *In* Datnoff, Snyder and Kornodörfer (ed.). Silicon in agriculture. Studies in Plant Science 8. Elsevier, Amsterdam.

Miller, B.S., R.J. Robinson, J.A. Johnson, E.T. Jones, and B.W.X. Ponnaiya. 1960. Studies on the relation between silica in wheat plants and resistance to Hessian fly attack. Journal of Economic Entomology. 53:995-999.

Nolla, A., G.H. Korndorfer, C.A.T Silva, T.R.B Silva, V. Zucarelli, and M.A.G Silva. 2013. Correcting soil acidity with the use of slags. African Journal of Agricultural Research. 8: 5174-5180.

Rafi, M.M. and E. Epstein. 1999. Silicon absorption by wheat (*Triticum aestivum* L.). Plant and Soil. 211:233-230.

Raid, R.N., D.L. Anderson, and M.F. Ulloa. 1992. Influence of cultivar and amendment of soil with calcium silicate slag on foliar disease development and yield of sugarcane. Crop Protection. 11(1):84-88.

Raven, J.A. 1983. The transport and function of silicon in plants. Biological Reviews. 58:179-207

Reitz, L.P. 1967. World distribution and importance of wheat. *In* K.S. Quisenberry and L.P. Reitz (ed.) Wheat and wheat improvement. 1st ed. American Society of Agronomy. 13:1-18. Madison, WI.

Rust Scoring Guide. Wageningen, Netherlands: Research Institute for Plant Protection , 198.

Saha, A.K. 2008. Methods of physical and chemical analysis of soil. Kalyani Publishers, India.

Saleh, J., N. Najafi, S. Oustan, N. Aliasgharzad, and K. Ghassemi-Golezani. 2013. Effects of silicon, salinity and water logging on the extractable Zn, Cu, K and Na in a sandy loam soil. International Journal Agricultural Research and Reviews. 3(1):56-64.

SAS. 2012. The SAS system for Windows. Version 9.3. Cary, NC: SAS Institute.

Savant, N.K., L.E. Datnoff, and G.H. Snyder. 1997. Depletion of plant-available silicon in soils: A possible cause of declining rice yields. Communications in Soil Science and Plant Analysis. 28:1245-1252.

Slaton, N. A., R. D. Cartwright, J. Meng, E. E. Gbur, and R. J. Norman. 2003. Sheath blight severity and rice yield as affected by nitrogen fertilizer rate, application method, and fungicide. Agronomy Journal. 95: 1489–1496.

Smolders, E. and J. Mertens. 2013. Cadmium. *In* B.J. Alloway (ed). Heavy Metals in Soils. Environmental Pollution 22. 3rd ed. Springer. 283-311.

Steinnes, E. 2013. Lead. *In* B.J. Alloway (ed). Heavy Metals in Soils. Environmental Pollution 22. 3rd ed. Springer. 395-409.

Tahir, M.A., Rahmatullah, T. Aziz, M. Ashraf, S. Kanwal, and M.A. Maqsood. 2006. Beneficial effects of silicon in wheat (*Triticum aestivum L.*) under salinity stress. Pakistan Journal of Botany. 38(5):1715-1722.

United States Department of Agriculture- Economic Research Service. 2014.Wheat/Background. Available on-line at http://www.ers.usda.gov/topics/crops/wheat/background.aspx. Verified February 18, 2015.

United States Department of Agriculture- National Agricultural Statistics Service. 2014.Quick Stats (U.S./states). Available on-line at http://quickstats.nass.usda.gov/results/A937E2FE-00A4-3B58-AE8A-E966194E251E.Verified February 18, 2015.

Wallace, A. 1989. Relationships among nitrogen, silicon, and heavy metal uptake by plants. Soil Science. 147(6): 457-460.

Weindorf, D.C. 2008. An update of the field guide to Louisiana soil classification. LSU AgCenter Bulletin 889. Louisiana Agriculture Experiment Station, Baton Rouge, LA.

Yoshida, S. 1981. "Fundamentals of rice crop science". International Rice Research Institute, Los Banos, Laguna, Philippines.

Chapter 3. Evaluation of the Interactive Effects of Silicon and Nitrogen on Disease Indices, Nutrient Uptake, Select Agronomic Parameters, and Wheat Yield Components.

3.1 Introduction

Silicon (Si) can provide yield increases to crops in numerous ways and these effects are more expressed when plants are under stress (Epstein, 1994). The ways in which Si can contribute to higher yields have been well-evaluated independently but little is known on the interaction between Si and other nutrients, more specifically with nitrogen (N) in wheat (*Triticum aestivum*) production. High amounts of N fertilizer can increase susceptibility to disease as observed by Slaton (2003) where N rates that achieved higher yields also increased the onset of sheath blight in rice. Wallace (1989) showed that SiO_2 concentrations decrease in plant tissue with increasing N. Decreased SiO_2 concentrations in plant tissue can increase susceptibility to fungal diseases (Volk et al., 1958). Alternately, Deren (1997) reported decreases in N and phosphorus (P) concentrations with applied Si in rice (*Oryza sativa*) plants. Also relating to the uptake of macronutrients, tissue potassium (K) has also shown to increase at high levels of applied Si by Gerami and Rameeh (2012) in rice.

Yield components have been evaluated for their contributions to yield increases as influenced by Si. In rice, Ma et al. (1989) reported increases in the number of panicles as well as spikelets per panicle with Si. They also showed that Si contributed to a large decrease in the number of blank spikelets. Increases in the weight of 1,000 grains were observed by Balasta et al. (1989)

and Gerami and Rameeh (2012) while no increases were seen by Ma et al. (1989). Gerami and Rameeh (2012) further reported significant N and Si interaction effects on panicle length, grain yield, and decreases in the number of un-filled grains. A study conducted by Mauad et al. (2003) showed that N fertilization increased the number of stems and panicles in rice while Si fertilization decreased the number of blank spikelets per panicle.

Agronomic parameters such as biomass and plant height are also affected by Si. Abro et al. (2009) observed increases in the height of wheat plants that had been fertilized with Si, however this was not the case in the study conducted by Mauad et al. (2003). Studying the effects of Si and metal tolerance in corn (*Zea mays*), Cunha and Nascimento (2009) observed increases in biomass production with added Si. Increases in biomass production were also seen by Gong et al. (2003) in wheat.

Nitrogen is the most limiting nutrient in non-leguminous crop production systems and consequently the most applied. Because of the important role and presence of N in crop nutrition, the interactions between N and Si are important to understand. Much of the research published on N and Si interactions has been with rice, but their interactions in wheat production need further study. Further documentation of the components that lead to yield increases in wheat are also necessary, specifically as they relate to N. This study was conducted to evaluate the interactive effects of silicon and nitrogen on disease indices, nutrient uptake, select agronomic parameters, and yield components of wheat.

3.2 Materials and Methods

3.2.1 Site Description, Treatment Structure, and Trial Establishment

This study was conducted at three site-years from 2012-2014 on Mississippi River alluvial soils. The first site-year was established on a Commerce silt loam soil (Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) in St. Joseph (Latitude 31°, 56’, 42.6” N; Longitude 91°, 13’, 34” W), located in the northeast region of Louisiana. Sites were established at two locations in 2013:(1) St. Joseph, Louisiana (Latitude 31°, 56’, 41.0” N; Longitude 91°, 13’, 25.8” W) on a field with Sharkey-Tunica-Newellton complex (Very-fine, smectitic, thermic Chromic Epiaquerts) and Commerce silt loam soil types and (2) Ben Hur Research farm in Baton Rouge (Latitude 30°, 21’, 40.4” N; Longitude 91°, 10’, 01.9” W) near Louisiana State University on a Cancienne silt loam soil (Fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquepts).

All three site-years were established and managed under a dryland, conventional tillage system. Dates of major field activities and plot sizes are summarized in Table 3.1. Initial soil properties can also be found summarized in Appendix A in Table A.1. The treatment structure contained two N rates x five $CaSiO_3$ slag rates arranged in a randomized complete block design with four replications. Each replication consisted of two control plots that did not receive any Si or N. One of these controls received lime at the rate of 4.5 MT ha^{-1} (Table 3.2) to differentiate between pH and treatment effects since the use of slags

Table 3.1. Record of trial establishment and field activities.

Location	Year Est.	Site-Year ID	Plot Size, m	Date					
				Si Application	Planting	N Application	Feekes 5 (BM1)	Feekes 10.5 (BM2)	Harvest
St. Joseph	2012	NERS 2013	1.5 x 5.2	9-Nov-12	9-Nov-12	1-Feb-13	14-Mar-13	17-Apr-13	7-Jun-13
St. Joseph	2013	NERS 2014	1.5 x 3.7 [1]	14-Nov-13	16-Nov-13	21-Feb-14	5-April-14 [2]	16-Apr-14	6-Jun-14
Ben Hur	2013	BH 2014	1.2 x 4.6	8-Nov-13	11-Nov-13	22-Feb-14	21-Mar-14	10-Apr-14	22-May-14

[1] plot sizes varied from 3.4 - 4.3 m

[2] BM1 was Feekes GS 9 for NERS 2014

increases soil pH. The two N rates were 101 and 145 kg ha^{-1} applied as urea (46% N). The 145 kg N ha^{-1} rate is considered an excessive rate for wheat production in LA while the 101 kg N ha^{-1} rate is the standard N rate for silt loam soils. Five $CaSiO_3$ slag rates of 0, 1, 2, 4.5, and 9 (0, 120, 240, 540, and 1080 kg Si ha^{-1}) were applied at each N rate. Recommendations for phosphorus (P) and potassium (K) applications based off soil test results from the LSU AgCenter's Soil Testing and Plant Analysis Laboratory were followed prior to trial establishment to ensure that neither were limiting. A calcium silicate slag material was used as the silicon source for this study (14% Si). As byproducts, slags often contain other elements and a list of known components in the material used can be found in Appendix A in Table A.2. Slag and lime treatments were broadcast applied by hand in November for each site and incorporated into the soil to a depth of about 7.5 cm. Within a week, winter wheat variety Terral 8525 was drill seeded at the rate of 101 kg ha^{-1} for NERS 2013 and 2014 and 113 kg ha^{-}1 for BH 2014. Standard weed management practices were followed according to LSU AgCenter. Urea was broadcast applied to appropriate plots by hand around Feekes growth stage (GS) 4 (Large, 1954).

3.2.2 Plant Height and Biomass Samples

Biomass samples and height measurements were taken around Feekes 5 (BM1) and 10.5 (BM2) growth stages. Height measurements were taken randomly in six different locations within each plot and an average was computed.

Table 3.2. Treatment structure description.

Treatment Number	N rate, kg ha^{-1}	$CaSiO_3$ slag, Mt ha^{-1}
1	0	0
2	0	0 + 4.5 Mt ha^{-1} lime
3	101	0
4	101	1
5	101	2
6	101	4.5
7	101	9
8	145	0
9	145	1
10	145	2
11	145	4.5
12	145	9

A meter-stick was placed at the soil surface and the tallest part of the plant in that location was recorded as the plant height. To collect biomass samples, a 30 cm section of biomass was cut from each end of the plot and combined to form one sample. Plants were cut about 1-2 cm above the soil surface and the cut was started about 30 cm from the edge of the plot to avoid a border effect. The positioning of where samples were taken within the plot was changed for each sampling period to avoid cutting the same area that had already been sampled. This also helped to maintain a good representative sampling from plots. Samples were taken in the same way for each sampling time, regardless of bare spots that may have existed within planted rows, to avoid sampling bias. Thirty-cm long PVC pipes were used as guides for cutting biomass samples. Biomass samples were placed in paper bags and oven dried at 55°C until thoroughly dried (about 5 days) in a forced convection oven (Despatch LBB series; model number

LBB2-18-1). The dry weight of biomass samples was then recorded prior to being cut into 2-4 cm pieces using pruning shears and ground for plant tissue analysis.

3.2.3 Concentration of Silicon and Plant Essential Nutrients on Biomass, Straw and Grain

3.2.3.a. Silicon content*.* A modified version of the Oven-Induced Digestion (OID) procedure according to Kraska and Breitenbeck was followed (2010). One hundred milligrams (100 mg) of plant tissue was weighed into new 50 mL centrifuge tubes. Five drops of octyl alcohol were added followed by 2 mL of 30% hydrogen peroxide (H_2O_2). Caps were loosely screwed on and then placed in a mechanical convection oven (Yamato; model number DKN600) for 30 minutes at 95°C. Then 4 mL of 50% sodium hydroxide (NaOH) was added to samples and they were placed back in the oven for 4 hours at 95°C. During this 4 hour period tubes were gently mixed using a vortex mixer every 15 minutes. After 4 hours 1 mL of 5 mM ammonium fluoride (NH_4F) was added and then vortexed. Finally, tubes were brought to a final volume of 50 mL with deionized (DI) water. Silicon content was determined using modified version of the Molybdenum Blue Colorimetry (MBC) procedure as described by Hallmark et al (1982). Two (2) mL of aliquot from the digested samples was pipetted into 50 mL centrifuge tubes. Ten (10) mL of 20% acetic acid was added to tubes and then gently swirled by hand for 10 seconds. Four (4) mL of 0.26 M ammonium molybdate was added and samples were left for 5 minutes. After sitting, 2 mL of 20% tartaric acid was added and tubes were swirled again for 10 seconds, followed by the addition of 2 mL of the reducing agent (0.5 mg 1-amino-2-naphthol-4-sulphonic acid + 1.0 g sodium sulfite + 30.0 g in DI water with a final volume of 250 mL). Tubes were then brought to a final volume of 30 mL using 20% acetic acid. Tubes were then capped and shaken very well. After 30 minutes, the absorbance reading was measured using a Hach DR 5000 spectrophotometer at 630 nm.

3.2.3.b. Plant tissue elemental composition analysis. A modified wet ashing procedure was performed to prepare samples for multi-element analysis (Jones et al.,1991). Plant tissue (0.5 g) was weighed onto a 5 x 5 cm piece of Kimwipe, enclosed, and placed into 100-mL digestion tubes. Five (5) mL of nitric acid (HNO_3) were added down the walls of the tubes to rinse off any plant tissue. After 50 minutes tubes were vortexed for 5 seconds and then placed in a digestion block set at 150-155°C (maintained for the duration of the digestion procedure) for 5 minutes. Tubes were then allowed to cool for 10 minutes before adding 3 mL of H_2O_2 and covered with small glass funnels. Tubes were then placed back on the digestion block for 2 hours and 45 minutes. Tubes were then removed, allowed to cool and vortexed and transferred to 15 mL centrifuge tubes. The solution was diluted to a final volume of 12.5 mL using DI water and then refrigerated until analysis by Inductively Couple Plasma (ICP) – Optical Emission Spectroscopy (OEM) to determine the concentration of plant nutrients and select heavy metals (Spectro Arcos; model number ARCOS FH12). Samples were filtered with Whatman No. 1 filter paper before analysis. Results obtained by ICP analysis (ug mL^{-1}) were multiplied by a conversion factor of 25 (12.5 mL / 0.5 g) to express concentration in ug g^{-1} or mg kg^{-1}. Elemental composition (mg kg^{-1}) was then divided by 1,000 and multiplied by yield (Mt ha^{-1}) to finally express uptake in kg ha^{-1}.

3.2.4 Total N

Total N was determined using a dry combustion method where 20 mg of ground plant tissue or grain was weighed into tin capsules and measured with a C:N analyzer (Elementar Americas Inc, Vario EL Cube).

3.2.5 Leaf Rust Infection Rate

Sites were monitored for leaf rust later in the growing season. Leaf rust began to show up in plants around Feekes GS 10.5 or 11 which was late April in 2013 and early May for both sites in 2014. Once enough leaf rust was present to establish a baseline of 2% fields were monitored weekly or bi-weekly for rust development and rated respectively. Plots were assigned a percentage scale where the percent of leaf coverage by rust pustules was recorded at 5% increments, or 2% where minimal. A model for the rating scale used can be found in Figure 3.1. Plots were rated by the same person throughout the experiment to maintain consistency with ratings. Six locations within plots were evaluated in order to derive an average rating. The entire plant was observed but the top two most leaves received the most scrutinizing.

3.2.6 Scanning Electron Microscopy (SEM) / Energy Dispersive X-ray Analysis (EDX)

The distribution of silica bodies expressed in % weight in leaf samples was conducted using SEM/EDX technology. Flag leaf samples were taken at random from plots during rust ratings for NERS 2014 and in conjunction with BM1 samplings for both sites in 2014 and stored in a standard refrigerator until analysis.

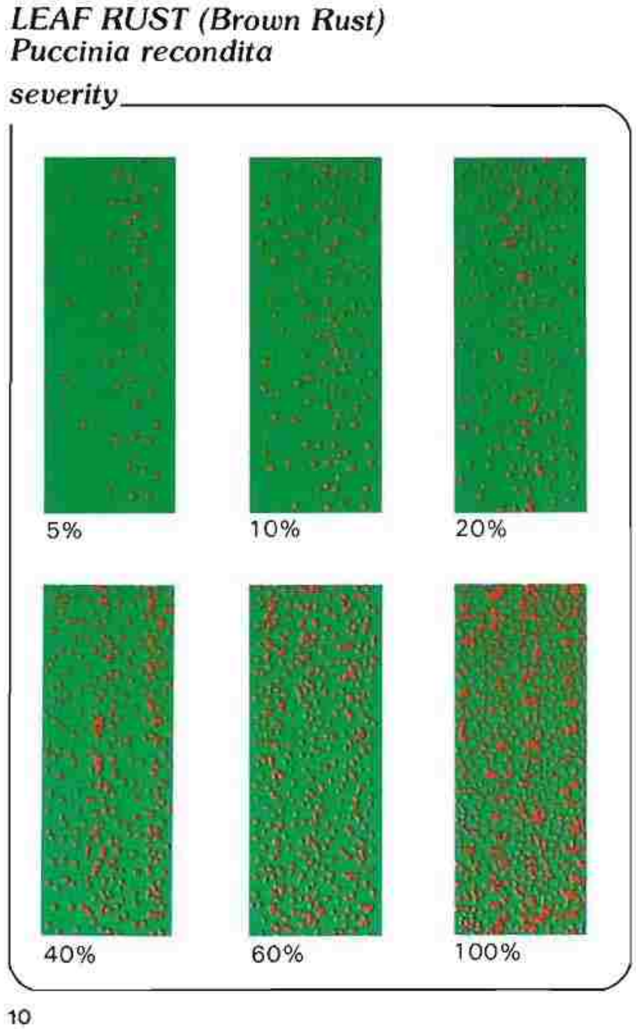


Figure 3.1 Image of grading scale for leaf rust (CIMMYT, 1986).

Small tissue samples were cut from the mid-section of the leaf just before analysis. Digital images were taken of leaf tissue and elemental composition of Si was determined using a SEM equipped with EDX capabilities (FEI Quanta 200 with EDAX SDD).

3.2.7 Grain Yield and Yield Components

A plot combine was used to harvest and collect grain subsamples for all three site years. NERS 2013 and 2014 were harvested with a Massey Ferguson

8XP combine while a Wintersteigher Classic plot harvester was used for BH 2014. Grain subsamples taken from each site during harvesting were analyzed for moisture content and test weight using a grain analysis computer (model number GAC2500 AGRI) prior to being weighed. Grain moisture content was adjusted to 12% and yield calculated in bushels per acre using the formula below:

$$\text{Grain Yield (bu/ac)} = \frac{\left[\dfrac{\text{grain weight (lbs/plot)}}{\text{plot size (ft}^2\text{)}} \times \dfrac{43{,}560\ \text{ft}^2}{\text{ac}}\right]\left[\dfrac{100 - \text{Moisture Content}}{88}\right]}{\text{Test Weight}}$$

Grain yield in bushels per acre was then converted to kg ha^{-1} using the formula:

$$\text{Grain Yield (kg ha}^{-1}\text{)} = \left[\frac{\text{Yield, bu}}{\text{ac}}\right] \times \frac{60\ \text{lbs}}{\text{bu}} \times \frac{1\ \text{kg}}{2.2\ \text{lbs}} \times \frac{2.47\ \text{ac}}{\text{ha}}$$

At maturity, similar sampling as BM1 and BM2 was done prior to plot harvesting for yield components. Prior to partitioning of straw and panicles, all tillers and panicles were counted for each sample. Once partitioned, each panicle was measured to obtain an average length and then all were combined and weighed for a total panicle weight. These panicles were later passed through a small bundle thresher (Almaco; model number SBT) and grain was obtained and weighed separately for grain weight. Straw was the only portion of the yield component samples that was ground and used for nutrient analysis, similar to BM1 and BM2. Grain subsamples were taken from the combine during plot harvesting and grain was analyzed for test weight and moisture content using a grain analysis computer (DICKEY-John GAC; model number GAC2500-AGRI). Grain from subsamples was used to obtain the weight of 1,000 grains and ground for analysis. One thousand grains (1,000) were counted using an Agriculex ESC-1 automated seed counter and then weighed.

The number of grains per panicle was also determined using the formula:

(Grain Yield) / (Panicles per Hectare) X (Seed Weight)

3.2.8 Soil Analysis

3.2.8.a. Extractable Silicon*.* One (1) gram of soil was weighed into 50 mL centrifuge tubes followed by the addition of 10 mL of 0.5 M acetic acid. Samples were immediately placed on a reciprocal shaker (Eberbach; model number E6010.00) for 1 hour. Immediately after shaking, samples were filtered with Whatman No. 1 filter paper (Korndorfer et al., 1999). Plant-available Si was determined by a modified Molybdenum Blue Colorimetry (MBC) procedure as outlined by Korndorfer et al. (2001). A 0.5 mL aliquot was pipetted into 50 mL centrifuge tubes. Ten mL of DI water was added followed by 0.5 mL of 1:1 HCl:DI water solution. One (1) mL of 10% ammonium molybdate ($\{NH_4\}_6Mo_7O_{24}{\cdot}4H_2O$) was added and samples were left to rest for 5 minutes. After resting, 1 mL of 20% tartaric acid was and tubes were gently swirled by hand for 10 seconds followed by another resting period of 2 minutes. One (1) mL of the reducing agent, ANSA, (0.5 mg 1-amino-2-naphthol-4-sulphonic acid + 1.0 g sodium sulfite + 30.0 g sodium bisulfite + DI water to a final volume of 250 mL) was added. DI water was then added to bring the samples to a final volume of 25 mL and tubes were capped and then shaken very well. After 5 minutes the absorbance reading was measured using a Hach DR 5000 spectrophotometer at 630 nm.

3.2.8.b. Extractable Nutrients by Mehlich-3 Procedure (Mehlich, 1984). Two (2) grams of soil was weighed into 100 mL plastic bottles followed by the addition of 20 mL of Mehlich-3 solution (dilute acid-fluoride-EDTA solution, pH 2.5). The samples were shaken on a reciprocal shaker set at high speed for 5 minutes and then filtered using Whatman No. 42 filter paper. The extract was then analyzed using Inductively Couple Plasma (ICP) – Optical Emission Spectroscopy (OEM) for essential nutrients and some heavy metals (Spectro Ciros CCD ICP analyzer).

3.2.8.c. Inorganic Nitrogen*.* Five (5) grams of soil was weighed into 100 mL plastic bottles and 35 mL of 1 M KCl was added. Bottles were shaken on a reciprocal shaker for 1 hour and then filtered with Whatman No. 42 filter paper. Sample extracts were measured simultaneously for nitrate and ammonium by a colorimetric method using an automated flow injection system (Lachat QuickChem 8500 series 2), similar to the method described by Keeney and Nelson (1982). Nitrate is converted to nitrite after passing through a cadmium column and then reacting with sulfanilamide, the coloring reagent, and measured at 520 nm. Ammonium was measured at 660 nm after a reaction with the salicylate-nitroprusside coloring reagent (Keeney and Nelson, 1982).

3.2.8.d. Soil pH (1:1 method). Five (5) grams of soil was weighed into 50 mL centrifuge tubes and 5 mL of DI water was added to each. Tubes were shaken on a reciprocal shaker for 1 hour and the pH was measured using an Oakton pH 5+ digital pH meter.

3.2.8.e. Total Soil Nitrogen. A dry combustion method was used to determine total N content of soil. Twenty (20) mg of soil was weighed into tin capsules and measured using a C:N analyzer (Elementar Americas Inc, Vario EL Cube).

3.2.9 Data Analysis

Analysis of variance was performed using PROC MIXED in SAS 9.3 to determine significant main effects of N, Si, and N x Si interactions on measured parameters (SAS, 2012). Nitrogen, Si, and their interaction were fixed effects while replications were considered a random effect. Treatments 1 and 2 were deleted and the program was run as a complete factorial in order to determine significant differences in Si treatments at each N rate. Difference of least square means (LSD) was then used to identify treatment differences.

3.4 Results and Discussion

3.4.1 Grain Yield

Wheat grain yield for all three sites and results of analysis of variance are summarized in Table 3.3. The effect of N on grain yield was significant across site-years (P<0.1) while Si effect was only significant at BH 2014 (P<0.1). At NERS 2013, plots applied with 101 kg ha^{-1} achieved higher grain yield (5222 kg ha^{-1}) than plots that received 145 kg N ha^{-1} (4933 kg ha^{-1}; P<0.1).

Conversely, higher grain yield was obtained from wheat applied with 145 kg N ha^{-1} for both sites in 2014 (P<0.01).

In BH 2014, the Si effect on grain yield was only significant when applied at the rate of 9 Mt CaSiO3 ha^{-1} across N application rates. There was no significant interaction effect of N and Si on grain yield across site-years. For NERS 2013 and BH 2014, at certain rates of N, $CaSiO_3$ application resulted in increased wheat grain yield. For NERS 2013, the highest overall yield of 5506 kg ha^{-1} was attained when 101 kg ha^{-1} N was combined with 2 Mt $CaSiO_3$ ha^{-1}. Grain yield obtained by this treatment combination was significantly higher than the control (no Si applied) and most of the Si-treated plots when applied with 145 kg N ha^{-1}. Compared with control, the application of 9 Mt $CaSiO_3$ ha^{-1} increased wheat grain yield by ~600 and ~700 kg ha^{-1} at N rates of 145 and 101 kg N ha^{-1}, respectively.

While results differed across site years, the increases in grain yields observed agree with reports of many others. Yoshida (1981) reported yield increases of 10% common with Si fertilization in rice production in Japan and Korea. Abro et al. (2009) observed increases in grain weight in wheat during a pot experiment when 5 g kg^{-1} of silicic acid was applied to pots. Tahir et al. (2006) also observed increases in grain yield of two wheat varieties using $CaSiO_3$ slag in Pakistan.

Table 3.3. Grain yield of wheat applied with varying rates of $CaSiO_3$ slag under sufficient and high N application rates for all sites.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Grain Yield, kg ha^{-1} NERS 2013	NERS 2014	BH 2014
	0	4841 bc	6384 cde	5177 e
	1	5240 abc	6517 bcde	5613 de
101	2	5506 a	5987 e	5674 de
	4.5	5370 ab	6472 bcde	5473 de
	9	5152 abc	6225 de	5905 cd
	mean	**5222 A**	**6317 B**	**5568 B**
	0	4881 bc	7410 ab	6519 b
	1	4736 c	7285 abc	6482 bc
145	2	4849 bc	6971 abc	6595 ab
	4.5	5209 abc	7568 a	6824 ab
	9	4991 bc	6868 abcd	7112 a
	mean	**4933 B**	**7220 A**	**6706 A**
Analysis of Variance				
N effect	*P*-value	<0.1	<0.001	<0.0001
Si effect	*P*-value	NS	NS	<0.1
N x Si Interaction	*P*-value	NS	NS	NS

[1]Means that share a common letter do not significantly differ from each other by Fisher's LSD (0.1) [2] Capital letters represent differences between N rates only (LSD-0.1).

3.4.2 Biomass Production and Plant Height

Nitrogen and Si effects on plant height and biomass production at Feekes 5 and 10.5 were evaluated across site-years (Tables 3.4, 3.5. and 3.6). Biomass was originally measured in grams per sampling area (m^2) but was converted to and expressed in Mt ha^{-1}. In these tables, straw yield and Si content of straw and grain were also reported. Using Fisher's LSD, means of these measured variables for each N and Si combination were compared. Across site years, higher rates of Si were seen to increase biomass and straw yields. A consistent effect of N on Si content of biomass and straw was observed (*P*<0.1). Wheat applied with the higher N rate of 145 kg N ha^{-1} had lower Si content in biomass and straw which can be partly attributed to dilution effect. These results are similar to those by Wallace (1989) where less SiO_2 was also found in plants when higher N rates were applied. Significant height differences among Si treatments were observed only at Feekes 5 while a N x Si interaction was only observed on biomass yield at Feekes 10.5. Increases on these measured variables were seen with applications of 1 Mt $CaSiO_3$ ha^{-1} to 9 Mt ha^{-1}. For NERS 2014 (Table 3.5), most measured variables were not affected by N, Si and their interaction. Similarly, there were only a few variables which showed significant response to N and Si for BH 2014 (Table 3.6). The effect of Si on biomass yield was only observed at Feekes 5 and at the lower N rate only (Table 3.6). Increases in biomass production were observed by Cunha and Nascimento (2009) in corn as well as in wheat by Gong et al. (2003). Nitrogen rate had no effect on plant height. However, at the lower N treatment, certain rates of $CaSiO_3$ showed positive effects on plant height. Plants were taller when Si was added at Feekes 5 and 10.5 for two of the three sites. Abro et al. (2009) observed increases in the height of wheat plants with Si fertilization. However, based only on the analysis of variance, results would agree more with Mauad et al. (2003) where Si had no effect on the height of rice plants.

3.4.3 Yield Components

Yield components were measured from samples collected prior to plot harvesting and expressed on a per-sampling area basis.

Table 3.4. Effects of varying rates of $CaSiO_3$ slag on biomass production and plant height at sufficient and high N application rates, NERS 2013.

		Feekes 5			Feekes 10.5			Harvest		
N	$CaSiO_3$	Yield	Si	Height	Yield	Si	Height	Straw	Si, %	
kg ha^{-1}	Mt ha^{-1}	Mt ha^{-1}	%	cm	Mt ha^{-1}	%	cm	Mt ha^{-1}	Straw	Grain
101	0	3.0 c	1.0 a	33 c	8.00 d	2.2 a	80 ab	7.0 bc	3.0 a	0.1 bc
	1	3.2 bc	0.9 abc	34 c	10.6 abc	2.0 ab	79 ab	7.2 bc	2.7 abc	0.1 abc
	2	4.1 a	0.9 ab	37 abc	8.50 d	2.1 ab	80 ab	8.1 ab	2.8 ab	0.1 ab
	4.5	2.9 abc	0.8 abcd	36 abc	8.70 abcd	2.0 ab	84 ab	7.9 ab	2.8 ab	0.1 ab
	9	4.1 ab	0.8 abc	40 a	11.2 a	2.2 ab	84 a	7.7 ab	2.9 ab	0.1 ab
145	0	3.6 abc	0.7 cd	35 c	11.2 ab	1.8 b	82 ab	7.1 bc	2.5 bc	0.1 a
	1	2.9 c	0.8 abcd	36 bc	10.6 abc	1.8 b	81 ab	8.0 ab	2.5 c	0.1 abc
	2	3.3 abc	0.8 abcd	34 c	8.40 cd	2.0 ab	76 b	7.5 bc	2.8 abc	0.1 ab
	4.5	3.4 abc	0.6 d	40 ab	10.8 abc	1.9 ab	84 a	6.3 c	2.7 abc	0.1 abc
	9	3.0 c	0.7 bcd	40 ab	9.40 bcd	2.0 ab	84 a	8.9 a	2.6 bc	0.0 c
Analysis of Variance										
N effect	*P*-value	NS	<0.01	NS	NS	<0.05	NS	NS	<0.05	NS
Si effect	*P*-value	NS	NS	0.05	NS	NS	NS	NS	NS	NS
N x Si Interaction	*P*-value	NS	NS	NS	<0.05	NS	NS	NS	NS	NS

[1]Means that share a common letter do not significantly differ from each other by Fisher's LSD (0.1) [2] NS = not significant.

Table 3.5. Effects of varying rates of $CaSiO_3$ slag on biomass production and plant height at sufficient and high N application rates, NERS 2014.

		Feekes 5			Feekes 10.5			Harvest		
N	$CaSiO_3$	Yield	Si	Height	Yield	Si	Height	Straw	Si, %	
kg ha^{-1}	Mt ha^{-1}	Mt ha^{-1}	%	cm	Mt ha^{-1}	%	cm	Mt ha^{-1}	Straw	Grain
101	0	4.8 a	2.0 a	57 a	9.00 abcd	1.5 ab	72 a	8.3 bc	3.1 a	0.02 abc
	1	4.9 a	2.4 a	59 a	7.70 cd	1.6 ab	75 a	7.3 c	3.0 a	0.01 c
	2	5.3 a	2.3 a	58 a	8.90 abcd	1.5 ab	73 a	8.7 abc	3.6 a	0.03 ab
	4.5	4.8 a	2.0 a	57 a	9.70 abc	1.5 ab	74 a	7.6 c	3.2 a	0.01 bc
	9	5.9 a	2.3 a	60 a	8.90 abcd	1.6 ab	75 a	9.8 ab	3.5 a	0.01 bc
145	0	5.0 a	2.1 a	59 a	10.7 a	1.6 ab	76 a	8.8 abc	3.2 a	0.01 bc
	1	5.5 a	2.3 a	59 a	7.50 d	1.7 a	76 a	8.4 abc	3.5 a	0.05 a
	2	5.8 a	2.1 a	58 a	10.3 ab	1.5 ab	76 a	8.4 abc	2.9 a	0.03 abc
	4.5	5.7 a	2.2 a	60 a	8.70 abcd	1.3 b	76 a	9.9 a	3.1 a	0.02 abc
	9	5.2 a	2.2 a	59 a	8.50 bcd	1.5 ab	76 a	7.3 c	3.1 a	0.01 c
Analysis of Variance										
N effect	*P*-value	NS	NS	NS	NS	NS	<0.1	NS	NS	NS
Si effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS
N x Si Interaction	*P*-value	NS	NS	NS	NS	NS	NS	<0.05	NS	NS

[1]Means that share a common letter do not significantly differ from each other by Fisher's LSD (0.1) [2] NS = not significant.

Table 3.6. Effects of varying rates of $CaSiO_3$ slag on biomass production and plant height at sufficient and high N application rates, BH 2014.

N	$CaSiO_3$	Feekes 5			Feekes 10.5			Harvest		
		Yield	Si	Height	Yield	Si	Height	Straw	Si, %	
kg ha^{-1}	Mt ha^{-1}	Mt ha^{-1}	%	cm	Mt ha^{-1}	%	cm	Mt ha^{-1}	Straw	Grain
101	0	2.3 b	1.3 c	41 b	7.4 a	1.6 b	79 bc	7.0 b	2.4 ab	0.06 ab
	1	3.7 a	1.6 ab	44 ab	7.1 a	1.7 ab	81 abc	8.2 b	2.5 ab	0.05 b
	2	3.1 a	1.5 bc	45 ab	7.4 a	1.6 b	79 c	8.4 ab	2.3 ab	0.08 a
	4.5	3.3 a	1.6 ab	45 ab	7.2 a	1.9 a	81 abc	8.5 ab	2.7 a	0.06 ab
	9	3.7 a	1.9 a	47 a	7.7 a	1.8 ab	83 a	7.5 b	2.2 ab	0.04 b
145	0	3.7 a	1.5 bc	45 ab	7.5 a	1.6 b	82 ab	8.7 ab	2.0 b	0.05 b
	1	3.1 a	1.6 ab	46 a	7.1 a	1.7 ab	82 ab	10.4 a	2.2 ab	0.05 b
	2	3.4 a	1.4 bc	45 ab	8.7 a	1.6 b	81 abc	10.4 a	2.0 b	0.04 b
	4.5	3.3 a	1.4 bc	47 a	7.5 a	1.5 b	82 ab	8.7 ab	2.2 ab	0.04 b
	9	3.5 a	1.6 ab	46 a	9.0 a	1.7 ab	83 a	8.5 ab	2.4 ab	0.05 b
Analysis of Variance										
N effect	*P*-value	NS	NS	NS	NS	NS	NS	<0.05	NS	NS
Si effect	*P*-value	NS	<0.05	NS	NS	NS	NS	NS	NS	NS
N x Si Interaction	*P*-value	<0.1	NS	NS	NS	NS	NS	NS	NS	NS

[1]Means that share a common letter do not significantly differ from each other by Fisher's LSD (0.1) [2] NS = not significant.

Significant effects of N and Si were observed on only few yield components (Tables 3.7 – 3.9). Results for the number of tillers showed a significant effect of N for BH 2014 (P<0.01), Si for NERS 2013 (P<0.05), and a significant N x Si interaction effect for NERS 2014 (P<0.05). This indicates that N and Si can both lead to increases in the number of tillers. An interaction existed at BH 2014 where at 2 Mt ha^{-1} of Si, more tillers were produced at the N rate of 101 kg ha^{-1} than at the higher rate of 145 kg ha^{-1} (P<0.05). Related to tiller production, significant interactions were observed in panicle number as well. An overall N x Si interaction effect was observed in NERS 2013 and NERS 2014 (P<0.1). In NERS 2013, there were a greater number of panicles and tillers when 9 Mt ha^{-1} of Si was applied vs 4.5 Mt ha^{-1} at the N rate of 145 kg ha^{-1}. Plots treated with 145 kg N ha^{-1} produced more panicles than plots treated with 101 kg N ha^{-1} at BH 2014 (P<0.05). Overall, N seemed to play a greater effect on this variable than Si. In rice, Mauad et al. (2003) reported that N had effects on the number of tillers and panicles but Si did not. Tamai and Ma (2008) also observed no differences in the number of tillers or panicles between low and high Si levels in rice plants. However, Si has been shown to increase panicle number by Ma et al. (1989) and tiller number by Gholami and Falah (2013). Increased N applications also influenced grain weight. Increased grain weight was recorded for plots at the N rate of 101 kg ha^{-1} vs 145 when 4.5 Mt of Si was applied (P<0.05) in NERS 2013. N and Si both displayed roles in increasing spike weight. In NERS 2013, the weight of spikes increased by about 13 grams when 2 Mt ha^{-1} of Si was applied vs 0 Si (P<0.05) while the higher N rate alone produced spikes that were

25 grams heavier than those of the lower rate at BH 2014. Increases in the weight of wheat spikes were reported by Ahmad et al. (2007) when evaluating Si effects on growth under water stress. Nitrogen and Si also influenced the weight of 1,000 grains (Table 3.7 and 3.9, respectively). While Si was shown to have no effect on 1,000 grain weight by Tamai and Ma (2008), the current results for this component agree with those of others (Gholami and Falah, 2013; Ahmad et al., 2013) where Si did improve 1,000 grain weight. Results of LSD analysis at 10% probability level showed effects of longer spikes at 2 Mt ha^{-1} Si compared to the control at 101 kg ha^{-1} N (Table 3.7). Silicon had an adverse effect, however, when the Si rate increased to 9 Mt ha^{-1} but this was not a significant difference. Increasing trends in spike length were observed by Ahmad et al. (2013) but differences were not significant. Many studies have identified that the number of blank spikelets on rice plants decrease when plants take up more Si (Tamai and Ma, 2008; Mauad et al, 2003; Gerami and Rameeh, 2012). The percentage of un-filled grains has been shown to decrease in barley plants as well (Ma and Takahashi, 2002). The percentage of un-filled grains is related to the number of grains per panicle and an indication of the overall fertility of spikes. The number of grains per spike was evaluated and significant increases were linked to grain yield increases at BH 2014 (Table 3.9). Increases in grains per spike were also observed in NERS 2014 and correlated with higher yields but not at significant levels. There is an abundance of evidence that Si can decrease transpiration rates in plants (Jones and Handreck, 1967; Gao et al., 2006; Ma

Table 3.7. Effects of varying rates of $CaSiO_3$ slag on yield components and grain yield at sufficient and high N application rates, NERS 2013.

			Yield Components						
N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Yield Mt ha^{-1}	Tiller #	Panicle #	1,000 grain wt (g)	Grains / spike	Grain wt (g)	Spike wt (g)	Spike Length(cm)
101	0	4.8 bc	66 bc	66 bc	33.25 a	16.9 c	62 bc	84 bc	7.2 bc
	1	5.2 abc	66 bc	65 bc	33.00 a	26.0 ab	68 ab	92 ab	7.4 abc
	2	5.5 a	71 ab	69 ab	33.00 a	26.3 ab	67 ab	99 a	7.6 a
	4.5	5.4 ab	67 bcd	70 bc	32.77 ab	27.0 ab	70 ab	95 abc	7.4 abc
	9	5.2 abc	70 abc	63 bc	32.5 ab	25.7 b	63 bc	87 abc	7.4 abc
145	0	4.9 bc	61 abc	62 bc	31.75 abc	28.7 ab	60 bc	82 bc	7.4 abc
	1	4.7 c	74 ab	70 ab	30.25 cd	24.0 b	69 ab	87 abc	7.3 abc
	2	4.8 bc	70 abc	70 ab	30.12 cd	25.1 b	67 ab	94 ab	7.5 ab
	4.5	5.2 abc	57 d	57 c	31.00 bcd	32.1 a	54 c	77 c	7.4 abc
	9	5.0 bc	76 a	76 a	29.75 d	24.4 b	74 a	96 ab	7.1 c
Analysis of Variance									
N Effect	*P*-value	<0.5	NS	NS	<0.001	NS	NS	NS	NS
Si Effect	*P*-value	NS	<0.05	NS	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	NS	<0.1	NS	<0.1	<0.1	NS	NS

[1]Means that share a common letter do not significantly differ from each other by Fisher's LSD (0.1).

Table 3.8. Effects of varying rates of $CaSiO_3$ slag on yield components and grain yield at sufficient and high N application rates, NERS 2014.

			Yield Components						
N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Yield Mt ha^{-1}	Tiller #	Panicle #	1,000 grain wt (g)	Grains / spike	Grain wt (g)	Spike wt (g)	Spike Length(cm)
101	0	6.4 cde	73 abcd	74 ab	35.75 b	26.6 abc	83 abc	109 bc	7 ab
	1	6.5 bcde	66 bcd	64 b	36.00 b	28.6 abc	76 c	100 c	7 ab
	2	6.0 e	76 abcd	76 ab	35.50 b	24.6 bc	85 abc	125 ab	7 b
	4.5	6.5 bcde	63 d	64 b	36.00 b	30.9 a	75 bc	98 c	6.9 b
	9	6.2 de	79 ab	78 a	37.00 a	24.3 c	89 ab	105 bc	7.3 ab
145	0	7.4 ab	77 abc	74 ab	36.00 b	28.7 abc	91 a	119 ab	7.3 ab
	1	7.3 abc	75 abcd	71 ab	36.00 b	29.4 abc	83 abc	110 bc	7.2 ab
	2	7.0 abc	73 abcd	73 ab	35.50 b	29.5 ab	82 abc	110 bc	6.9 b
	4.5	7.6 a	84 a	82 a	35.75 b	27.2 abc	94 a	134 a	7.4 a
	9	6.9 abcd	63 cd	64 b	36.25 ab	29.7 abc	72 c	95 c	7.1 ab
Analysis of Variance									
N Effect	*P*-value	<0.001	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	NS	NS	NS	<0.5	NS	NS	NS	NS
N x Si Effect	P-value	NS	<0.05	<0.1	NS	NS	<0.1	<0.05	NS

[1]Means that share a common letter do not significantly differ from each other by Fisher's LSD (0.1).

Table 3.9. Effects of varying rates of $CaSiO_3$ slag on yield components and grain yield at sufficient and high N application rates, BH 2014.

			Yield Components						
N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Yield Mt ha^{-1}	Tiller #	Panicle #	1,000 grain wt (g)	Grains / spike	Grain wt (g)	Spike wt (g)	Spike Length(cm)
101	0	5.2 e	53 bc	53 bc	36.75 c	33.4 ab	70 bc	80 e	7.1 bc
	1	5.6 de	48 c	49 c	37.00 bc	30.7 b	66 c	85 de	7.1 c
	2	5.7 de	55 bc	55 bc	36.75 c	30.4 b	77 bc	100 bcde	7.4 abc
	4.5	5.5 de	55 bc	56 bc	37.50 abc	29.5 b	76 bc	98 bcde	7.5 abc
	9	5.9 cd	52 c	51 c	38.00 a	39.8 a	65 c	94 cde	7.5 abc
145	0	6.5 b	60 abc	60 abc	37.50 abc	31.9 b	85 ab	114 abc	7.4 abc
	1	6.5 bc	70 a	69 a	37.75 ab	28.2 b	94 a	123 a	7.7 ab
	2	6.6 ab	69 a	70 a	37.00 bc	29.1 b	91 a	121 ab	7.7 a
	4.5	6.8 ab	55 bc	55 bc	38.25 a	33.4 ab	82 abc	109 abcd	7.5 abc
	9	7.1 a	67 ab	67 ab	37.50 abc	30.5 b	92 ab	116 abc	7.5 abc
Analysis of Variance									
N Effect	*P*-value	<0.0001	<0.01	<0.01	<0.1	NS	<0.001	<0.001	<0.1
Si Effect	*P*-value	<0.1	NS	NS	<0.1	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS

[1]Means that share a common letter do not significantly differ from each other by Fisher's LSD (0.1).

and Takahashi, 2002). In a study comparing a high Si accumulating rice variety with a low Si accumulating mutant type, Tamai and Ma (2008) again observed this correlation. They concluded that the ability of Si to decrease transpiration rates is partly due to the strengthening of cuticle layers that surround grains, allowing less moisture to evaporate that is needed for grain filling. It would be logical then to believe that this benefit of Si could lead to improvements in other parameters like grain or spike weight. With several of the yield components evaluated showing effects of Si fertilization; it is possible that decreased transpiration rates influenced these parameters as well as the number of grains per spike.

3.4.4 Elemental Composition and Uptake

A summary of tissue concentrations of Si, N, and various extractable nutrients of straw and grain samples can be found in Appendix A (Tables A.1 – A.9). Effects of N and Si were observed but only a significant overall N x Si interaction was observed for boron (B) in NERS 2013 and BH 2013 (Table A.2 and A.8 respectively). Higher N rates produce greater tillering so more "diluted" concentrations of elements can be expected at the higher N rate while simultaneously observing greater plant uptake amounts. Effects of N on tissue concentrations in straw were seen for aluminum (Al), arsenic (As), calcium (Ca), copper (Cu), iron (Fe), lead (Pb), magnesium (Mg), phosphorus (P), potassium (K), sulfur (S), zinc (Zn), Si, and N. The higher N application caused increases in concentrations of As, Ca, Cu, K, S, Zn, and N while increases in Al, Fe, Pb, Mg, P, and Si were observed at the lower N rate of 101 kg ha^{-1}. There was a smaller amount of Si in plants treated with higher N (Table A.2). This trend was also observed by Wallace (1989). The lower N rate of 101 kg N ha^{-1} caused increases in Mg, Mn, P, K, and Se in grain as well where the higher N rate resulted in increases in Ca, S, and N. Increased Si rates alone caused increases in straw concentrations of Pb, molybdenum (Mo), P, and S while a strong decrease in manganese (Mn) concentration was observed at higher Si rates. The strongest correlation between N or Si and any of the elements evaluated existed between Si and Mn as they maintained a significant, antagonistic relationship for all three sites for concentration and uptake in straw ($P<0.05$). Decreases in Mn tissue concentration and uptake with applied Si have been observed by others (Vlamis and Williams, 1967; Tavakkoli et al., 2011). These significant trends between Mn and Si were observed in grain as well. Higher Si rates increased grain concentration of Al, Ca, Mo, S, and N. The results for P disagree with the results of Deren (1997), who found that P concentrations decreased with applied Si. Along with P, it was found that decreasing N concentrations correlated with applied Si but that was not observed in this study. Applied Si has also been shown to increase tissue K by others but no significant correlation was found between Si and K here (Gerami and Rameeh, 2012). More significant N x Si interaction effects existed for the uptake of elements rather than tissue concentrations and most of these were found for NERS 2014 site (Tables 3.13-3.15). Plant uptake data is summarized in Tables 3.10 – 3.18. At the Si rate of 4.5 Mt ha^{-1}, increased uptake was observed for the following elements at the 145 kg ha^{-1} N rate vs the 101 kg ha^{-1} rate: Al, Ca, Cu, Fe, Ni, P, K, Na, S, Si, and N. Alternately, when the Si rate was increased to 9 Mt ha^{-1}, uptake of Cu, Ca, Mg,

Table 3.10. Effects of varying rates of Si and N fertilization on the uptake of macronutrients in wheat grain and straw samples at harvest, NERS 2013.

		Macronutrients, kg ha^{-1}											
N	$CaSiO_3$	N		P		K		Ca		Mg		S	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	60	94	5.2	8.1	59.4	9.0	21.6	1.0	7.9	2.9	5.0	2.5
	1	66	89	5.4	7.5	63.9	8.6	25.3	1.0	8.6	2.6	6.2	2.5
	2	60	100	5.8	7.4	66.6	8.4	24.2	1.0	9.2	2.6	6.1	2.4
	4.5	64	95	5.9	8.1	70.7	9.1	26.5	1.0	9.6	2.8	6.8	2.5
	9	66	93	5.8	8.6	60.8	9.7	24.2	1.2	8.8	3.1	7.3	2.6
145	0	62	93	4.8	7.4	53.8	8.3	21.1	0.9	7.3	2.6	5.5	2.4
	1	75	75	4.9	6.9	57.6	8.1	21.9	1.1	7.9	2.5	5.6	2.3
	2	69	91	5.3	7.9	63.8	9.0	23.3	1.1	8.3	2.8	5.8	2.4
	4.5	60	97	4.9	7.1	55.8	7.6	21.6	0.9	8.0	2.5	6.0	2.6
	9	70	97	6.8	7.5	74.0	8.2	27.6	1.0	10.0	2.6	8.2	2.7
Analysis of Variance													
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	<0.05	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]NS= Non-significant.

Table 3.11. Effects of varying rates of Si and N fertilization on the uptake of Si and micronutrients in wheat grain and straw at harvest, NERS 2013.

N	$CaSiO_3$	Si, kg ha^{-1}		Micronutrients, kg ha^{-1}									
				Zn		Mn		Fe		Cu		B	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	212	3.4	0.26	0.07	0.78	0.11	1.5	0.09	0.09	0.02	0.04	0.01
	1	191	3.7	0.27	0.06	0.63	0.09	2.5	0.08	0.08	0.01	0.06	0.03
	2	235	4.3	0.22	0.06	0.55	0.08	2.4	0.09	0.09	0.01	0.05	0.01
	4.5	209	3.7	0.15	0.07	0.56	0.09	3.4	0.08	0.08	0.03	0.09	0.01
	9	227	3.6	0.16	0.08	0.39	0.09	2.1	0.08	0.08	0.01	0.04	0.01
145	0	190	3.8	0.25	0.06	0.79	0.10	2.4	0.10	0.10	0.01	0.04	0.01
	1	211	2.9	0.19	0.06	0.66	0.09	2.4	0.10	0.10	0.03	0.02	0.01
	2	210	3.5	0.32	0.06	0.50	0.08	2.4	0.06	0.06	0.01	0.04	0.02
	4.5	143	3.6	0.30	0.06	0.49	0.08	1.4	0.09	0.09	0.01	0.05	0.02
	9	237	2.4	0.39	0.06	0.36	0.07	2.5	0.07	0.07	0.01	0.04	0.02
Analysis of Variance													
N Effect	*P*-value	NS	NS	<0.1	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	NS	NS	NS	NS	<0.001	<0.01	NS	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]NS= Non-significant.

Table 3.12. Effects of varying rates of Si and N fertilization on the uptake of micronutrients and metals in wheat grain and straw at harvest, NERS 2013.

		kg ha^{-1}			
N	$CaSiO_3$	Mo		Al	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain
101	0	0.01	0.00	2.3	0.00
	1	0.00	0.00	3.8	0.01
	2	0.01	0.01	3.5	0.00
	4.5	0.00	0.01	5.3	0.00
	9	0.00	0.00	3.2	0.00
145	0	0.00	0.00	3.3	0.00
	1	0.01	0.00	3.6	0.00
	2	0.01	0.00	3.7	0.00
	4.5	0.00	0.00	2.1	0.00
	9	0.02	0.01	3.6	0.01
Analysis of Variance					
N Effect	*P*-value	NS	NS	NS	NS
Si Effect	*P*-value	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	NS	NS	NS

[1]NS= Non-significant. [2] Data either not available or NS for elements not shown.

Ni, P, Si, and N increased at the 101 N rate vs the 145 kg ha^{-1} N rate. For all Si rates except for the highest of 9 Mt ha^{-1}, elements with significantly higher uptake values were always seen in conjunction with the higher N rate showing that N strongly influences the uptake of essential nutrients. Significant increases in uptake of Fe, Mo, and S in straw existed with increased Si rates. Increases in P uptake in straw have been observed by Tavakkoli et al. (2011). Results for straw P do not agree with those by Tavakkoli but significant increases in P uptake were observed in grain ($P<0.05$) (Table 3.16).

Table 3.13. Effects of varying rates of Si and N fertilization on the uptake of macronutrients in wheat grain and straw at harvest, NERS 2014.

		Macronutrients, kg ha^{-1}											
N	$CaSiO_3$	N		P		K		Ca		Mg		S	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	65	110	5.1	36.0	50.6	14.1	17.3	2.0	7.0	7.6	5.3	11.6
	1	45	111	4.4	42.4	41.4	16.7	15.9	2.1	6.3	9.0	4.9	11.9
	2	57	98	5.2	35.4	35.6	13.9	17.6	1.8	7.2	7.4	5.9	10.5
	4.5	44	108	4.5	41.0	41.0	16.4	15.3	2.1	6.3	8.7	4.8	12.1
	9	64	104	7.5	41.7	57.2	15.8	21.8	2.1	9.3	9.0	7.4	11.8
145	0	59	122	6.2	42.6	58.0	16.1	19.5	2.3	7.5	9.2	6.2	13.1
	1	51	135	6.8	41.4	59.3	15.8	19.8	2.2	7.3	8.9	7.0	13.3
	2	61	114	4.3	42.2	59.4	16.4	18.7	2.3	6.8	9.1	6.2	13.5
	4.5	84	128	7.7	44.0	68.6	17.3	24.1	2.4	8.8	9.2	8.2	13.6
	9	48	121	4.9	43.8	44.9	16.9	17.6	2.3	6.9	9.5	6.0	13.3
Analysis of Variance													
N Effect	*P*-value	NS	<0.001	NS	NS	<0.01	NS	<0.05	<0.01	NS	<0.1	<0.05	<0.001
Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	<0.01	NS	<0.01	NS	<0.05	NS	<0.05	NS	<0.05	NS	0.05	NS

[1]NS= Non-significant.

Table 3.14.Effects of varying rates of Si and N fertilization on the uptake of Si and micronutrients in wheat grain and straw at harvest, NERS 2014.

				Micronutrients, kg ha^{-1}									
N	$CaSiO_3$	Si kg ha^{-1}		Zn		Mn		Fe		Cu		B	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	281	1.3	0.00	0.2	1.0	0.4	0.7	0.2	0.01	0.02	0.05	0.09
	1	185	0.5	0.00	0.3	1.0	0.4	0.7	0.3	0.01	0.02	0.09	0.11
	2	261	2.9	0.00	0.2	0.8	0.3	1.1	0.2	0.01	0.02	0.08	0.09
	4.5	243	0.9	0.00	0.3	0.7	0.4	0.9	0.3	0.01	0.03	0.03	0.01
	9	341	0.6	0.00	0.3	0.8	0.3	1.2	0.3	0.01	0.03	0.03	0.09
145	0	285	1.2	0.00	0.3	1.1	0.4	1.0	0.3	0.01	0.03	0.04	0.09
	1	294	4.7	0.01	0.3	0.9	0.4	1.0	0.3	0.01	0.03	0.03	0.07
	2	246	1.1	0.00	0.3	1.0	0.4	0.8	0.3	0.01	0.03	0.05	0.03
	4.5	350	2.1	0.00	0.3	0.9	0.4	1.4	0.3	0.02	0.03	0.06	0.05
	9	227	0.5	0.00	0.3	0.6	0.3	0.9	0.3	0.01	0.03	0.05	0.06
Analysis of Variance													
N Effect	*P*-value	NS	NS	NS	<0.01	NS	NS	NS	<0.05	NS	NS	NS	NS
Si Effect	*P*-value	NS	NS	NS	NS	<0.05	NS	NS	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	<0.001	<0.05	NS	NS	NS	NS	<0.1	NS	<0.05	NS	NS	NS

[1]NS= Non-significant.

Table 3.15. Effects of varying rates of Si and N fertilization on the uptake of micronutrients and metals in wheat grain and straw at harvest, NERS 2014.

		kg ha^{-1}											
N	$CaSiO_3$	Mo		Ni		Se		Al		As		Pb	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	0.00	0	0.01	0.01	0.01	0	0.6	0.00	0.01	0.01	0	0
	1	0.00	0	0.01	0.01	0.01	0	0.6	0.01	0.01	0.01	0	0
	2	0.00	0	0.01	0.01	0.01	0	1.0	0.01	0.01	0.01	0	0
	4.5	0.00	0	0.01	0.01	0.01	0	0.6	0.00	0.01	0.01	0	0
	9	0.01	0	0.01	0.01	0.01	0	1.1	0.02	0.01	0.01	0	0
145	0	0.00	0	0.01	0.01	0.01	0	0.9	0.01	0.01	0.02	0	0
	1	0.00	0	0.01	0.01	0.01	0	0.8	0.02	0.01	0.01	0	0
	2	0.00	0	0.01	0.01	0.01	0	0.7	0.01	0.01	0.01	0	0
	4.5	0.00	0	0.01	0.01	0.01	0	1.3	0.00	0.01	0.01	0	0
	9	0.00	0	0.01	0.01	0.01	0	0.8	0.01	0.01	0.01	0	0
Analysis of Variance													
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	NS	<0.1	NS	NS	NS	<0.01	NS	NS	NS	NS	NS

[1]NS= Non-significant.

Table 3.16. Effects of varying rates of Si and N fertilization on the uptake of macronutrients in wheat grain and straw at harvest, BH 2014.

N	$CaSiO_3$	Macronutrients, kg ha^{-1}											
		N		P		K		Ca		Mg		S	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	33	76	3.5	36	44	17	11	1.8	4.5	7.9	3.7	8.1
	1	30	83	4.3	37	55	17	12	1.9	5.5	7.9	4.3	8.8
	2	40	84	5.0	37	50	17	14	1.9	5.8	7.9	4.5	8.8
	4.5	42	82	4.4	40	54	18	14	2.0	6.1	8.4	4.6	9.0
	9	34	93	4.5	42	50	19	11	2.3	5.2	9.0	4.1	10.7
145	0	42	102	3.6	41	56	19	14	2.2	5.5	8.8	4.4	10.4
	1	44	105	4.2	40	71	19	16	2.2	6.6	8.6	5.1	10.6
	2	49	102	3.3	39	74	18	15	2.1	6.3	8.3	4.9	10.3
	4.5	43	108	4.0	45	58	20	15	2.4	5.9	9.6	4.5	11.2
	9	50	120	4.6	48	53	22	16	2.5	5.7	10.3	4.7	12.1
Analysis of Variance													
N Effect	*P*-value	0.01	<0.001	NS	<0.01	<0.01	<0.01	<0.05	<0.001	NS	<0.01	NS	<0.001
Si Effect	*P*-value	NS	<0.01	NS	<0.05	NS	<0.05	NS	<0.05	NS	<0.05	NS	<0.01
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]NS= Non-significant.

Table 3.17.Effects of varying rates of Si and N fertilization on the uptake of Si and micronutrients in wheat grain and straw at harvest, BH 2014.

N	$CaSiO_3$	Si kg ha^{-1}		Micronutrients, kg ha^{-1}									
				Zn		Mn		Fe		Cu		B	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	138	2.2	0	0.2	0.6	0.3	0.8	0.10	0.01	0.02	0.03	0.04
	1	202	2.6	0	0.2	0.5	0.3	0.7	0.10	0.01	0.02	0.03	0.04
	2	193	4.4	0	0.2	0.5	0.3	0.8	0.09	0.01	0.02	0.12	0.04
	4.5	240	3.1	0	0.2	0.3	0.2	1.5	0.11	0.01	0.02	0.12	0.02
	9	161	2.2	0	0.2	0.2	0.3	0.9	0.10	0.01	0.03	0.08	0.05
145	0	176	3.2	0	0.2	0.7	0.4	0.6	0.11	0.01	0.03	0.06	0.03
	1	226	3.2	0	0.2	0.5	0.3	1.0	0.09	0.01	0.03	0.17	0.04
	2	244	2.6	0	0.2	0.6	0.3	0.7	0.10	0.01	0.02	0.03	0.01
	4.5	192	3.0	0	0.3	0.3	0.3	1.0	0.13	0.01	0.03	0.06	0.08
	9	211	3.4	0	0.3	0.3	0.3	0.9	0.13	0.01	0.03	0.08	0.03
Analysis of Variance													
N Effect	*P*-value	NS	NS	NS	<0.01	NS	<0.05	NS	NS	NS	<0.05	NS	NS
Si Effect	*P*-value	NS	NS	NS	NS	<0.001	<0.05	<0.1	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	<0.05	NS	NS	NS	NS	NS	NS	NS	NS	<0.1	<0.1

[1]NS= Non-significant.

Table 3.18. Effects of varying rates of Si and N fertilization on the uptake of micronutrients and metals in wheat grain and straw at harvest, BH 2014.

N	$CaSiO_3$	kg ha^{-1}											
		Mo		Ni		Se		Al		As		Pb	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	0.00	0.00	0.01	0.01	0.01	0.003	0.58	0	0.01	0.01	0.00	0
	1	0.00	0.00	0.01	0.01	0.00	0.003	0.60	0	0.01	0.01	0.00	0
	2	0.01	0.01	0.02	0.01	0.01	0.004	0.69	0	0.01	0.01	0.00	0
	4.5	0.01	0.01	0.02	0.01	0.01	0.002	0.69	0	0.01	0.01	0.00	0
	9	0.01	0.01	0.01	0.01	0.00	0.004	0.85	0	0.01	0.01	0.00	0
145	0	0.00	0.00	0.01	0.01	0.01	0.005	0.51	0	0.01	0.01	0.00	0
	1	0.00	0.00	0.02	0.01	0.01	0.003	0.86	0	0.01	0.01	0.00	0
	2	0.00	0.00	0.02	0.01	0.01	0.004	0.49	0	0.02	0.01	0.00	0
	4.5	0.01	0.01	0.02	0.01	0.01	0.005	0.87	0	0.01	0.01	0.01	0
	9	0.01	0.01	0.02	0.01	0.01	0.005	0.83	0	0.01	0.01	0.00	0
Analysis of Variance													
N Effect	*P*-value	NS	NS	<0.1	NS	NS	<0.01	NS	NS	<0.01	<0.01	NS	NS
Si Effect	*P*-value	<0.05	<0.01	NS	0.05	NS	NS	NS	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]NS= Non-significant.

3.4.5 Leaf Rust

Leaf Rust (caused by the fungus *Puccinia triticina*), is perhaps the worst and most prevalent disease affecting wheat throughout the state of Louisiana (Groth et al., 2013). The disease, however, was not severe during the two years of this study and extensive data on this component was not able to be collected. However, ratings were able to be conducted once for NERS 2013 and 2014. Only N showed a significant main effect on this variable (Table 3.19). At NERS 2013 the 145 kg ha^{-1} N rate corresponded with a mean rating of 19 while the 101 kg ha^{-1} N rate corresponded with a mean of 12. These results agree with the findings reported by Slaton et al. (2003) and many others that high N rates can lead to increased occurrence of disease. Figure 3.2 shows the rust ratings of leaves treated at various N and Si rates. Higher rust ratings were seen in plots treated with the higher N rate of 145 kg ha^{-1}, however, these higher readings also corresponded to higher Si treatments. The data available showed variable effects of Si treatments on rust ratings but trends tended to show greater leaf coverage when more Si was applied, contrary to what was expected. However, these results for Si effects were not found to be significant.

3.4.6 SEM

The distribution of silica bodies expressed in % weight in leaf samples was conducted using SEM/EDX technology. A strong visual distribution of Si bodies was hard to determine and no strong correlation was found between the presence of proposed Si bodies in photos and leaf samples from Si treated plots. Samples that were not treated with Si sometimes showed as many or more proposed Si bodies than those not treated with Si. The concentrations of Si determined by wet digestion in biomass samples was not significantly different between Si treated and non-Si treated plots. This could explain the lack of differences among treatments in observable SiO_2 in leaves. The %Si determined by EDX was also not correlated with results from the wet digestion procedure used to determine %Si in the lab.

Table 3.19. Influence of N and Si rates on percentage of leaf rust coverage for all sites.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	% Leaf Rust Coverage NERS 2013	NERS 2014	BH 2014
101	0	11 d	10 b	-
	1	13 cd	10 b	-
	2	11 cd	19 a	-
	4.5	13 cd	11 b	-
	9	14 bcd	13 ab	-
	mean	**12 B**	**13 A**	-
145	0	14 bcd	11 b	-
	1	18 abc	16 ab	-
	2	18 abc	11 b	-
	4.5	24 a	14 ab	-
	9	20 ab	15 ab	-
	mean	**19 A**	**14 A**	-
Analysis of Variance				
N Effect	*P*-value	0.01	NS	-
Si Effect	*P*-value	NS	NS	-
N x Si Effect	*P*-value	NS	NS	-

[1]Means that share a common letter do not significantly differ from each other by Fisher's LSD (0.1) [2] Capital letters represent differences between N rates only (LSD-0.1) [3]No ratings were taken for BH 2014.

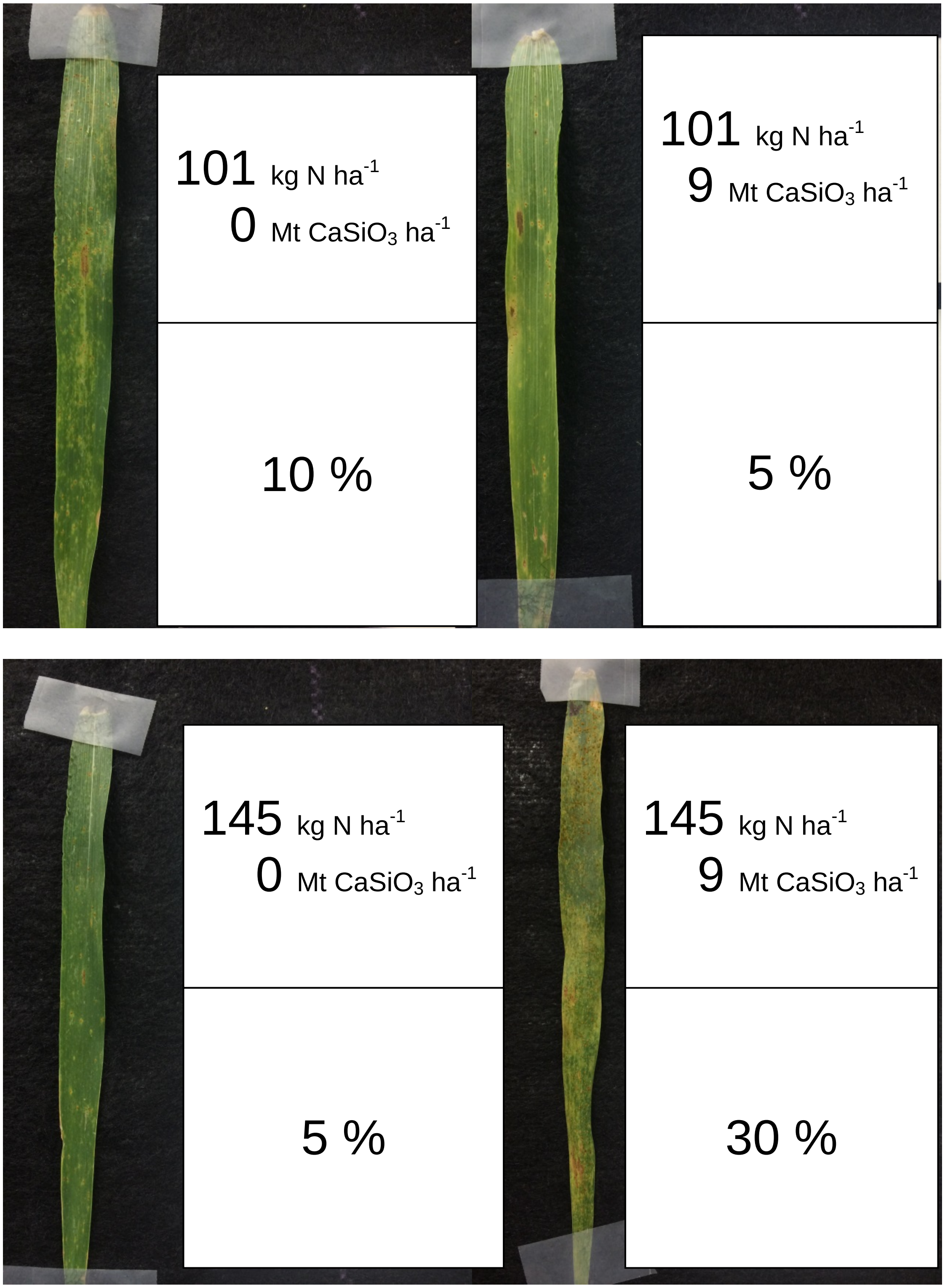


Figure 3.2. Leaf samples showing percent coverage of leaf rust at varying N and Si treatments. NERS 2014, Feekes 11. Ratings shown represent the entire plot.

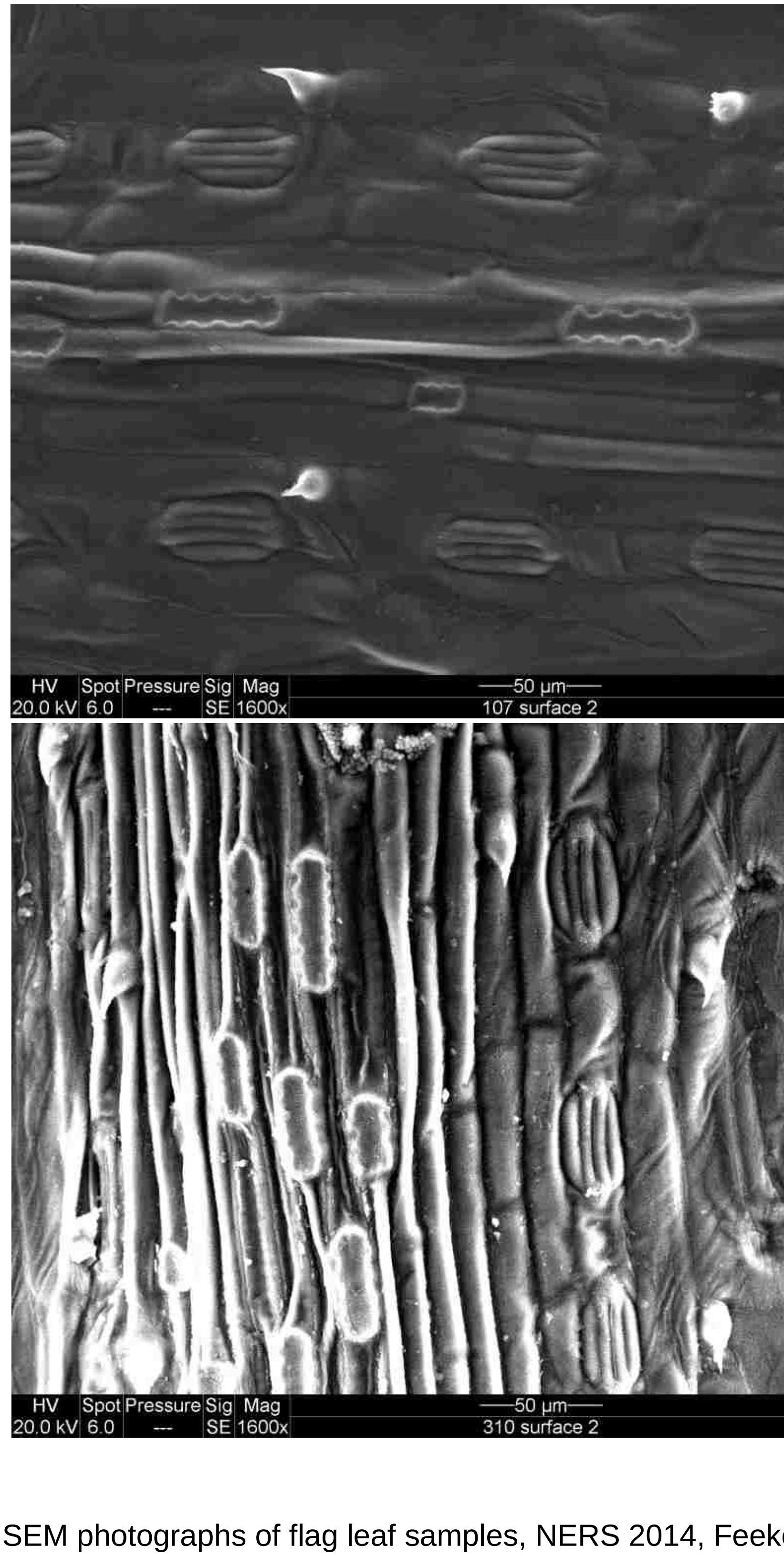


Figure 3.3 SEM photographs of flag leaf samples, NERS 2014, Feekes 11. A-Treatment 1 (0 N, 0 Si); B-Treatment 7 (101 N kg ha^{-1}, 9 Si Mt ha^{-1}).

3.4.7 Soil pH and Extractable Nutrients

Soil samples taken at midseason and harvest were analyzed for 0.5 M acetic acid extractable Si, Mehlich-3 extractable nutrients, and soil pH. $CaSiO_3$ was effective at increasing soil Si and increased the soil pH. Nitrogen and Si showed effects on the availability of some essential nutrients and heavy metals. Results for analysis of soil samples can be found in Appendix B and C (midseason and harvest, respectively).

3.5 Conclusions

Significant effects of N and Si were observed on grain yield. Higher yields were achieved at the 101 kg ha^{-1} N rate for one site while the other two sites displayed higher yields at the 145 kg ha^{-1} N rate (P<0.1). Several parameters were evaluated to determine their involvement in these yield increases. Firstly, disease pressure from leaf rust was not very severe during the two years of this study and adequate data was not able to be collected. Secondly, very minimal lodging effects were observed. With minor leaf rust presence and no significant Si effects in the data able to be collected, a confident conclusion can be made that yield increases did not arise from increased resistance to leaf rust and certainly not from lodging damage. The evaluated variables left that could contribute to yield increases were biomass production, plant height, yield components, and the uptake of other nutrients. Nitrogen and Si had significant effects on all these variables making it difficult to determine the exact component responsible for yield increases. Significant differences between Si treatments at both N rates for yield components were found. In NERS 2013, significant increases in the number of grains per spike, spike weight, and spike length were all observed at higher Si rates. At the N rate of 101 kg ha-1, increases in these three yield components were linked to grain yield increases (Table 3.7). The weight of 1,000 grains component was linked to grain yield increases in BH 2014 (Table 3.9). Increases in various extractable nutrients were observed as well as greater uptake of nutrients such as P and S in plant tissue. The increased availability of nutrients in the soil and their uptake could play a role in improved yields. Results suggest that all these factors contribute to yield increases in their own ways. Climatic factors, various stresses, and soil factors may influence which parameters the effects of Si can be observed in under different circumstances. While further research could be useful to further identify specific parameters, these results will help elucidate the components that contribute to grain yield increases in wheat production brought about by Si fertilization.

3.6 References

Abro, S.A., R. Qureshi, F.M. Soomro, A.A. Mirbahar, and G.S. Jakhar. 2009. Effects of silicon levels on growth and yield of wheat in silty loam soil. Pakistan Journal of Botany. 41:1985-1390.

Agarie, S., H. Uchida, W. Agata, F. Kubota, and P.B. Kaufman. 1998. Effects of silicon on transpiration and leaf conductance in rice plants (*Oryza sativa L*). Plant Production Science. 1(2):89-95.

Ahmad, A., M. Afzal, A.U.H. Ahmad, and M. Tahir. 2013. Effect of foliar application of silicon on yield and quality of rice (*Oryza sativa L*). Cercetări Agronomice în Moldova. XLVI, No. 3(155) 21-28.

Ahmad, F., Rahmatullah, T. Aziz, M.A. Maqsood, M.A. Tahir, and S. Kanwal. 2007. Effect of silicon application on wheat (*Triticum aestivum* L.) growth under water deficiency stress. Emirates Journal of Food and Agriculture. 19(2):01-07.

Balasta, M.L.F.C., C.M. Perez, B.O. Juliano, C.P. Villareal, J.N.A. Lott, and D.B. Roxas. 1989. Effects of silica level on some properties of *Oryza sativa* straw and hull. Canadian Journal of Botany. 67:2356-2363.

CIMMYT (International Maize and Wheat Improvement Center). 1986. Rust scoring guide. Wageningen, Netherlands: Research Institute for Plant Protection.

Cunha, K. and C. Nascimento. 2009. Silicon effects on metal tolerance and structural changes in maize (*Zea mays* L.) grown on a cadmium and zinc enriched soil. Water, Air & Soil Pollution. 197:323-330.

Deren, C.W. 1997. Changes in nitrogen and phosphorus concentrations of silicon-fertilized rice grown on organic soil. Journal of Plant Nutrition. 20(6):765-771.

Epstein, E. 1994. The anomaly of silicon in plant biology. Proceedings of the National Academy of Sciences. 91:11-17.

Epstein, E. 1999. Silicon. Annual Review of Plant Physiology and Plant Molecular Biology. 50:641-664.

Gao, X., C. Zou, L. Wang, and F. Zhang. 2006. Silicon decreases transpiration rate and conductance from stomata of maize plants. Journal of Plant Nutrition. 29: 1637-1647.

Gerami, M. and V. Rameeh. 2012. Study of silicon and nitrogen effects on yield components and shoot ions nutrient composition in rice. Agriculture (Pol'nohospodárstvo). 58:93-98.

Gholami, Y. and A. Falah. 2013. Effects of two different sources of silicon on dry matter production, yield and yield components of rice, Tarom Hashemi variety and 843 lines. International Journal of Agriculture and Crop Science. 5(3)227-231.

Gong, H., K. Chen, G. Chen, S. Wang, and C. Zhang. 2003. Effects of silicon on growth of wheat under drought. Journal of Plant Nutrition. 26(5):1055-1063.

Groth, D.,Hollier, C.A., and Padgett, G.B. 2013. Leaf rust of wheat. Louisiana Plant Pathology Series. Publicaiton 3248.

Hallmark, C. T., L. P. Wilding, and N.E. Smeck. 1982. Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. 15:263-274.

Jones, J.B., B. Wolf, and H.A. Mills. 1991. Plant Analysis Handbook. Micro-Macro Publishing. 23-26.

Jones, L.H.P. and Handreck, K.A.1967. Silica in soils, plants, and animals. Advances in Agronomy. 19:107-149.

Keeney D. R. and D.W. Nelson. 1982. Nitrogen-Inorganic forms. Methods of Soil Analysis, part 2. 9:643-698.

Korndörfer, G. H., G.H. Snyder, M. Ulloa, G. Powell, and L.E. Datnoff. 2001. Calibration of soil and plant silicon analysis for rice production. Journal of Plant Nutrition. 24:7, 1071 – 1084.

Korndorfer, G. H., N. M. Coelho, G. H. Snyder, and C. T. Mizutani. 1999. Avaliacao de metodos de extracao de silicio em solos cultivados com arroz de sequeiro. Revista Brasileira de Ciencia do Solo. 23:101-106.

Kraska, J.E., and G.A Breitenbeck. 2010. Simple robust method for quantifying silicon in plant tissue. Communications in Soil Science and Plant Analysis. 41:2075-2085.

Large, E.C. 1954. Growth stages in cereals: Illustration of Feekes scale. Plant Pathology. 3:128-129.

Ma, J.F., and E. Takahashi. 2002. Soil, fertilizer, and plant silicon research in Japan. Elsevier, Amsterdam.

Ma, J.F., K. Nishimura, and E. Takahashi. 1989. Effect of silicon on the growth of rice plant at different growth stages. Soil Science and Plant Nutrition. 35:347-356.

Mauad, M., C.A.C. Crusciol, H.G. Filho, and J.C. Correa. 2003. Nitrogen and silicon fertilization of upland rice. Scientia Agricola. 60:761-765.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Communications in Soil Science Plant Analysis. 15:1409-1416.

SAS. 2012. The SAS system for Windows. Version 9.3. Cary, NC: SAS Institute.

Slaton, N. A., R. D. Cartwright, J. Meng, E. E. Gbur, and R. J. Norman. 2003. Sheath blight severity and rice yield as affected by nitrogen fertilizer rate, application method, and fungicide. Agronomy Journal. 95: 1489–1496.

Tahir, M.A., Rahmatullah, T. Aziz, M. Ashraf, S. Kanwal, and M.A. Maqsood. 2006. Beneficial effects of silicon in wheat (*Triticum aestivum L.*) under salinity stress. Pakistan Journal of Botany. 38(5):1715-1722.

Tamai, K. and J.F. Ma. 2008. Reexamination of silicon effects on rice growth and production under field conditions using a low silicon mutant. Plant and Soil. 307:21-27.

Tavakkoli, E., P. English, and C.N. Guppy. 2011. Interaction of silicon and phosphorus mitigate manganese toxicity in rice in a highly weathered soil. Communications in Soil Science and Plant Analysis. 42:503-513.

Vlamis, J. and D.E. Williams. 1967. Manganese and silicon interaction in the gramineae. Plant and Soil. XXVII, no. 1:131-140.

Volk, R.J., R.P. Kahn, and R.L. Weintraub. 1958. Silicon content of the rice plant as a factor influencing its resistance to infection by the blast fungus, *piricularia-oryzae.* Phytopathology. 48:179-184.

Wallace, A. 1989. Relationships among nitrogen, silicon, and heavy metal uptake by plants. Soil Science. 147(6): 457-460.

Yoshida, S. 1981. “Fundamentals of rice crop science”. International Rice Research Institute, Los Banos, Laguna, Philippines.

Chapter 4. Conclusions

Nitrogen and Si both positively influenced wheat grain yields. Higher grain yields were achieved at 101 kg N ha^{-1} in NERS 2013 but higher yields were observed at 145 kg N ha^{-1} in the other two site years. $CaSiO_3$ slag was effective at increasing the 0.5 M acetic acid extractable Si and increases in pH were observed with increasing Si. Leaf rust was not as prevalent during the two years of this study and substantial data was unable to be collected. Very minimal lodging was observed in fields during this study as well. This would suggest however that yield increases must have come from parameters other than disease or lodging resistance. With several yield components showing effects of Si, it is difficult to conclude exactly which ones are responsible for yield increases. It is possible and results would suggest that improvements can manifest in different yield components under certain circumstances. This could be a result of climatic conditions such as heat or water stress or more complex soil related factors. Results of yield component measurements do indicate that Si plays a role in growth and development. Furthering this notion is the influence of Si on plant height and straw production observed. With results showing increases in the uptake of certain nutrients like P and S in straw with Si fertilization, it is also possible that the improved growth parameters and yield components are indirect effects of enhanced nutrition. The increased availability of other nutrients as a result of $CaSiO_3$ slag fertilization may contribute to yield increases. Ma and Takahashi (2002), Gao et al. (2006), and others have concluded that Si fertilization can lead to decreased transpiration. Tamai and Ma (2008) determined that decreased transpiration rates were responsible for greater percentages of filled grains because of a thickened cuticle layer surrounding grains allowing less water loss. Others believe the decrease in transpiration rates from Si may be due to the direct factors of transpiration like leaf conductance or stomatal movement (Agarie et al., 1998). In either view, transpiration rates could be the cause of improvements in yield components, plant height, and biomass production. These parameters as well as the uptake of essential nutrients are likely contributors to grain yield increases in wheat production in Louisiana. More research is needed to validate the current findings but these results will help elucidate the links between grain yield increases in wheat and the components responsible for them.

Appendix A. Initial Soil Properties and $CaSiO_3$ Slag Composition

Table A.1. Initial soil properties of all sites.

	Extractable Nutrients, mg kg^{-1}								Total, %				
	Si	P	K	Ca	Mg	S	Cu	Zn	N	C	Organic Matter,%	Soil Class	pH
NERS 2013	62	138	401	2136	604	133	3.2	2.5	.14	1.2	2.3	silt loam	5.66
NERS 2014	49	40	309	2212	625	20	3.3	1.9	.16	1.3	2.1	silt loam	5.27
BH 2014	48	35	146	1833	481	17	1.8	1.0	.14	0.9	1.5	silt loam	6.13

[1]Extractable nutrients determined Mehlich- 3 extraction and ICP. [2]Silicon determined by 0.5 M acetic acid extraction and MBC. [3]Percent C and N determined by dry combustion. [4]Organic matter determined by Walkley and Black method, colorimetrically.

Table A.2. $CaSiO_3$ slag composition.

Element	Percent
Aluminum	7
Calcium	23
Iron	14
Magnesium	7
Manganese	1.6
Silicon	14
Sulfur	0.5

$CaSiO_3$ slag samples were sent to a private lab for analysis. [1]Silicon determined by HNO_3-HCl block digestion and ICP. [2]All other elements determined by HNO_3-HCl microwave digestion and ICP.

Appendix B. Tissue Concentration of Nutrients and Metals in Wheat Grain and Straw at Harvest

Table B.1. Effects of varying rates of Si and N fertilization on the concentration of macronutrients in wheat grain and straw at harvest, NERS 2013.

		Macronutrients, %											
N	$CaSiO_3$	N		P		K		Ca		Mg		S	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	0.67	1.8	0.06	0.15	0.65	0.17	0.24	0.018	0.09	0.05	0.06	0.05
	1	0.68	1.8	0.06	0.15	0.68	0.17	0.27	0.020	0.09	0.05	0.07	0.05
	2	0.64	1.8	0.05	0.15	0.62	0.17	0.23	0.019	0.09	0.05	0.06	0.05
	4.5	0.63	1.8	0.06	0.15	0.70	0.17	0.26	0.018	0.10	0.05	0.07	0.05
	9	0.67	1.8	0.06	0.17	0.63	0.19	0.24	0.023	0.09	0.06	0.07	0.05
145	0	0.71	1.9	0.05	0.15	0.63	0.17	0.24	0.018	0.08	0.05	0.06	0.05
	1	0.72	1.9	0.05	0.15	0.61	0.18	0.23	0.024	0.08	0.06	0.06	0.05
	2	0.69	1.9	0.05	0.16	0.64	0.19	0.23	0.022	0.08	0.06	0.06	0.05
	4.5	0.71	1.9	0.06	0.14	0.65	0.15	0.25	0.017	0.09	0.05	0.07	0.05
	9	0.73	2.0	0.06	0.15	0.69	0.17	0.26	0.020	0.09	0.05	0.08	0.05
Analysis of Variance													
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.01	NS
Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	0.05	NS	NS	NS	0.1
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	0.1	NS	NS	NS	NS	NS	NS

[1]NS= Non-significant.

Table B.2. Effects of varying rates of Si and N fertilization on the concentration of Si micronutrients in wheat grain and straw at harvest, NERS 2013.

				Micronutrients, mg kg^{-1}									
N	$CaSiO_3$	Si, %		Zn		Mn		Fe		Cu		B	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
	0	3.0	0.06	29	13	91	21	168	17	14	1.7	4.5	2.7
	1	2.7	0.06	28	13	65	17	268	16	17	1.6	7.2	6.3
101	2	2.8	0.07	20	12	53	16	228	17	12	2.2	4.2	2.1
	4.5	2.8	0.07	15	13	56	16	335	15	14	1.6	8.7	2.8
	9	2.9	0.07	17	16	40	17	201	16	11	2.1	3.7	2.2
	0	2.5	0.08	28	13	88	20	270	21	18	2.2	4.8	2.7
	1	2.5	0.06	20	13	68	19	291	22	14	2.3	2.7	1.5
145	2	2.8	0.07	33	13	50	17	243	13	15	1.6	3.6	4.8
	4.5	2.7	0.07	37	12	58	15	156	17	12	1.6	6.3	3.0
	9	2.6	0.05	34	13	33	13	240	14	21	1.7	4.0	3.4
Analysis of Variance													
N Effect	P-value	<0.05	NS	<0.05	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	P-value	NS	NS	NS	NS	<0.001	<0.01	NS	NS	NS	NS	NS	NS
N x Si Effect	P-value	NS	NS	NS	NS	NS	<0.1	NS	NS	NS	0.1	NS	<0.01

[1]NS= Non-significant.

Table B.3. Effects of varying rates of Si and N fertilization on the concentration of micronutrients and metals in wheat grain and straw at harvest, NERS 2013.

		mg kg^{-1}			
N	$CaSiO_3$	Mo		Al	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain
101	0	0.8	0.3	265	0.0
	1	0.4	0.5	410	1.5
	2	0.9	0.3	336	0.1
	4.5	0.2	0.4	525	0.0
	9	0.3	0.4	310	0.1
145	0	0.0	0.3	380	0.0
	1	0.8	0.4	437	1.1
	2	1.2	0.2	374	0.7
	4.5	0.5	0.2	232	0.2
	9	1.9	0.4	346	1.0
Analysis of Variance					
N Effect	*P*-value	NS	NS	NS	NS
Si Effect	*P*-value	NS	NS	NS	<0.1
N x Si Effect	*P*-value	NS	NS	NS	NS

[1]NS= Non-significant. [2] Data either not available or NS for elements not shown.

Table B.4. Effects of varying rates of Si and N fertilization on the concentration of macronutrients in wheat grain and straw at harvest, NERS 2014.

N	$CaSiO_3$	Macronutrients, %											
		N		P		K		Ca		Mg		S	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	0.65	1.7	0.06	0.57	0.60	0.22	0.21	0.03	0.08	0.12	0.06	0.18
	1	0.61	1.7	0.06	0.66	0.56	0.26	0.21	0.03	0.09	0.14	0.07	0.18
	2	0.64	1.6	0.06	0.60	0.53	0.23	0.20	0.03	0.08	0.13	0.07	0.18
	4.5	0.57	1.7	0.06	0.64	0.54	0.25	0.20	0.03	0.08	0.14	0.06	0.19
	9	0.66	1.7	0.08	0.68	0.57	0.26	0.22	0.03	0.09	0.15	0.08	0.19
145	0	0.67	1.8	0.07	0.61	0.65	0.23	0.22	0.03	0.09	0.13	0.07	0.19
	1	0.76	1.9	0.08	0.61	0.69	0.23	0.24	0.03	0.09	0.13	0.08	0.20
	2	0.70	1.8	0.07	0.61	0.69	0.24	0.22	0.03	0.08	0.13	0.07	0.19
	4.5	0.75	1.8	0.08	0.61	0.69	0.24	0.24	0.03	0.09	0.13	0.08	0.19
	9	0.66	1.8	0.07	0.64	0.61	0.25	0.24	0.03	0.09	0.14	0.08	0.19
Analysis of Variance													
N Effect	*P*-value	0.05	<0.001	NS	NS	<0.001	NS	<0.05	NS	NS	NS	<0.01	<0.01
Si Effect	*P*-value	NS	<0.05	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	<0.1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]NS= Non-significant.

Table B.5. Effects of varying rates of Si and N fertilization on the concentration of Si micronutrients in wheat grain and straw at harvest, NERS 2014.

				Micronutrients, mg kg^{-1}									
N	$CaSiO_3$	Si, %		Zn		Mn		Fe		Cu		B	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	3.1	0.02	0.04	35	126	60	145	34	1.4	3.4	6.5	13.0
	1	3.0	0.01	0.00	40	143	66	94	42	1.3	3.8	5.3	15.0
	2	3.6	0.03	0.27	37	98	55	127	36	1.3	3.7	10.0	14.1
	4.5	3.2	0.01	0.00	40	94	58	110	40	1.3	4.1	4.8	2.1
	9	3.5	0.01	0.22	45	83	55	120	45	1.5	4.3	12.2	14.1
145	0	3.2	0.01	0.33	40	124	63	111	43	1.5	3.7	5.0	12.6
	1	3.5	0.05	0.56	42	103	58	116	39	1.6	3.9	3.8	11.1
	2	2.9	0.03	0.41	41	117	59	98	41	1.5	3.7	6.2	3.9
	4.5	3.1	0.02	0.16	40	92	57	148	39	1.5	3.9	6.7	7.9
	9	3.1	0.01	0.00	43	78	51	126	40	1.5	3.9	6.7	8.2
Analysis of Variance													
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	<0.01	NS	NS	NS
Si Effect	*P*-value	NS	NS	NS	NS	<0.05	NS	NS	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]NS= Non-significant.

Table B.6. Effects of varying rates of Si and N fertilization on the concentration of micronutrients and metals in wheat grain and straw at harvest, NERS 2014.

		mg kg^{-1}											
N	$CaSiO_3$	Mo		Ni		Se		Al		As		Pb	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	0.25	0.05	1.3	1.6	0.67	0.17	107	0.4	1.2	1.7	0.27	0
	1	0.24	0.50	1.4	1.9	0.75	0.24	83	1.8	1.3	1.9	0.39	0
	2	0.30	0.01	1.6	1.8	0.92	0.44	114	1.8	1.2	2.0	0.27	0
	4.5	0.24	0.09	1.4	1.9	0.77	0.08	78	0.1	1.4	1.5	0.66	0
	9	0.52	0.63	1.5	1.8	1.22	0.26	274	2.1	1.2	1.9	0.43	0
145	0	0.22	0.16	1.6	2.0	0.79	0.21	97	1.7	1.3	2.2	0.23	0
	1	0.25	0.05	1.5	1.7	0.99	0.03	99	2.7	1.3	1.8	0.12	0
	2	0.29	0.30	1.4	1.7	0.85	0.12	84	1.4	1.2	1.5	0.00	0
	4.5	0.33	0.22	1.4	1.6	0.94	0.13	134	0.2	1.2	1.3	0.43	0
	9	0.49	0.25	1.5	1.5	0.93	0.07	109	1.1	1.4	1.7	0.00	0
Analysis of Variance													
N Effect	*P*-value	NS	NS	NS	NS	NS	<0.05	NS	NS	NS	NS	<0.01	NS
Si Effect	*P*-value	<0.05	NS	NS	NS	NS	NS	NS	<0.1	NS	<0.05	<0.1	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]NS= Non-significant.

Table B.7. Effects of varying rates of Si and N fertilization on the concentration of macronutrients in wheat grain and straw at harvest, BH 2014.

		Macronutrients, %											
N	$CaSiO_3$	N		P		K		Ca		Mg		S	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	0.49	1.5	0.06	0.71	0.62	0.33	0.15	0.04	0.07	0.15	0.05	0.16
	1	0.43	1.5	0.05	0.66	0.65	0.30	0.14	0.03	0.07	0.14	0.05	0.16
	2	0.48	1.5	0.06	0.65	0.60	0.30	0.16	0.03	0.07	0.14	0.05	0.15
	4.5	0.50	1.5	0.05	0.71	0.62	0.33	0.16	0.04	0.07	0.15	0.05	0.16
	9	0.45	1.6	0.06	0.65	0.67	0.30	0.15	0.03	0.07	0.14	0.06	0.16
145	0	0.49	1.6	0.04	0.63	0.64	0.30	0.16	0.03	0.06	0.13	0.05	0.16
	1	0.48	1.6	0.04	0.62	0.68	0.29	0.16	0.03	0.06	0.13	0.05	0.16
	2	0.47	1.5	0.03	0.58	0.71	0.28	0.14	0.03	0.06	0.13	0.05	0.16
	4.5	0.49	1.6	0.05	0.66	0.67	0.30	0.17	0.04	0.07	0.14	0.05	0.16
	9	0.49	1.7	0.06	0.67	0.64	0.30	0.15	0.03	0.07	0.14	0.06	0.17
Analysis of Variance													
N Effect	*P*-value	NS	<0.001	<0.01	<0.01	<0.05	<0.05	NS	<0.1	<0.05	<0.05	NS	NS
Si Effect	*P*-value	NS	<0.001	<0.1	<0.1	NS	<0.1	NS	<0.05	NS	NS	NS	<0.01
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	<0.05	NS	NS	NS	NS

[1]NS= Non-significant.

Table B.8. Effects of varying rates of Si and N fertilization on the concentration of Si micronutrients in wheat grain and straw at harvest, BH 2014.

				Micronutrients, mg kg^{-1}									
N	$CaSiO_3$	Si, %		Zn		Mn		Fe		Cu		B	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	2.4	0.06	ND	38	84	59	122	21	1.3	4.2	5.6	6.9
	1	2.5	0.05	ND	36	61	49	87	17	1.1	4.1	3.6	7.4
	2	2.3	0.08	ND	35	64	46	155	16	1.3	4.1	13.9	6.5
	4.5	2.7	0.06	ND	37	38	45	162	20	1.2	4.3	13.0	3.4
	9	2.2	0.04	ND	33	31	39	134	15	1.2	4.0	10.4	8.0
145	0	2.0	0.05	ND	34	85	56	72	16	1.1	3.9	7.0	4.5
	1	2.2	0.05	ND	37	52	44	102	14	1.2	4.1	15.3	7.4
	2	2.0	0.04	ND	31	58	43	67	15	1.1	3.8	3.6	1.7
	4.5	2.2	0.04	ND	37	33	42	112	18	1.2	4.1	6.9	11.5
	9	2.4	0.05	ND	38	38	38	105	18	1.1	4.1	9.3	4.5
Analysis of Variance													
N Effect	*P*-value	NS	NS	NS	NS	NS	<0.1	<0.05	NS	NS	NS	NS	NS
Si Effect	*P*-value	NS	NS	NS	NS	<0.001	<0.001	NS	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	<0.1	<0.1

[1]NS= Non-significant. [2] ND= Non-detectable.

Table B.9. Effects of varying rates of Si and N fertilization on the concentration of macronutrients in wheat grain and straw at harvest, BH 2014.

N	$CaSiO_3$	mg kg^{-1}											
		Mo		Ni		Se		Al		As		Pb	
kg ha^{-1}	Mt ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
101	0	0.4	0.5	1.4	1.6	0.76	0.59	85.4	0.0	1.4	1.5	0.19	0
	1	0.5	0.5	1.6	1.3	0.52	0.50	74.9	0.3	1.3	1.6	0.47	0
	2	0.7	1.2	1.8	1.2	0.92	0.68	129.9	0.0	1.3	1.7	0.33	0
	4.5	0.9	0.9	2.0	1.2	0.80	0.35	110.9	0.4	1.3	1.4	0.51	0
	9	1.3	1.3	1.8	0.9	0.67	0.59	121.5	0.1	1.2	1.8	0.47	0
145	0	0.3	0.2	1.5	1.4	0.59	0.73	59.0	0.3	1.4	1.7	0.31	0
	1	0.4	0.6	1.8	1.1	0.66	0.48	89.0	0.3	1.3	1.8	0.37	0
	2	0.3	0.6	1.5	1.2	0.66	0.54	45.4	0.0	1.5	1.5	0.18	0
	4.5	0.9	0.9	1.8	1.1	0.60	0.72	99.4	0.2	1.4	1.8	0.70	0
	9	1.0	1.2	1.7	0.9	0.89	0.66	94.4	0.4	1.5	1.6	0.19	0
Analysis of Variance													
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	<0.1	NS	<0.05	NS	NS	NS
Si Effect	*P*-value	<0.001	<0.01	NS	<0.01	NS	NS	NS	NS	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]NS= Non-significant.

Appendix C. Extractable Nutrients and pH of Midseason Soil Samples

Table C.1. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH, 0.5 M acetic acid extractable-Si, soil NH_4^+ and NO_3^-, and Mehlich-3 extractable macronutrients, NERS 2013, midseason soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Silicon and Macronutrients, mg kg^{-1}							
			Si	NH_4	NO_3	P	K	Ca	Mg	S
0	0	5.4	54	10.6	0.6	42	292	2093	523	9
0	0+lime	6.3	80	10.1	1.2	38	271	2308	531	9
101	0	5.7	52	11.1	1.2	35	249	1943	500	8
	1	5.6	62	10.7	1.5	35	251	2111	532	8
	2	5.7	58	11.0	0.4	36	242	2108	523	9
	4.5	6.2	104	11.5	1.8	39	269	2463	578	9
	9	6.6	144	12.0	1.4	42	248	2609	576	14
145	0	5.3	51	12.7	1.3	40	258	1979	491	9
	1	5.6	58	14.1	2.8	41	250	2065	502	8
	2	5.8	76	14.0	1.0	42	263	2106	524	9
	4.5	6.0	94	11.5	0.9	41	265	2350	564	9
	9	6.5	141	13.8	1.5	40	252	2681	605	12
Analysis of Variance										
N Effect	*P*-value	NS	NS	<0.01	NS	<0.05	NS	NS	NS	NS
Si Effect	*P*-value	<0.001	<0.001	NS	NS	NS	NS	<0.001	<0.001	<0.001
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table C.2. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH and Mehlich-3 extractable micronutrients and metals, NERS 2013, midseason soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Micronutrients and Metals, mg kg^{-1}							
			Cu	Fe	Mn	Ni	Se	Al	Cr	Pb
0	0	5.4	2.5	439	142	3.5	0.03	776	0.10	2.4
0	0+lime	6.3	2.4	397	143	3.0	0.02	673	0.09	2.4
101	0	5.7	2.3	405	151	3.3	0.06	705	0.08	2.4
	1	5.6	2.5	415	147	3.3	0.02	736	0.10	2.4
	2	5.7	2.5	414	149	3.3	0.06	755	0.15	2.3
	4.5	6.2	2.7	408	142	3.1	0.00	793	0.21	2.6
	9	6.6	2.5	401	146	3.0	0.03	813	0.36	2.5
145	0	5.3	2.4	458	144	3.5	0.02	752	0.10	2.4
	1	5.6	2.5	430	140	3.3	0.02	752	0.12	2.4
	2	5.8	2.4	436	150	3.2	0.04	757	0.13	2.6
	4.5	6.0	2.6	412	147	3.4	0.04	776	0.21	2.5
	9	6.5	2.7	398	146	3.1	0.03	827	0.33	2.5
Analysis of Variance										
N Effect	*P*-value	NS	NS	<0.01	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.0001	<0.01	NS	NS	NS	NS	<0.001	<0.0001	<0.1
N x Si Effect	*P*-value	NS	NS	NS	NS	<0.1	NS	NS	NS	<0.1

[1]Zn levels were very low and are not shown.

Table C.3. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH, 0.5 M acetic acid extractable-Si, Soil NH_4^+ and NO_3^-, and mehlich-3 extractable macronutrients, NERS 2014, midseason soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Silicon and Macronutrients, mg kg^{-1} Si	NH_4	NO_3	P	K	Ca	Mg	S
0	0	4.9	47	14	0.6	45	358	2256	557	8
0	0+lime	5.3	58	12	0.8	36	341	2849	621	7
101	0	4.9	41	14	0.8	44	364	2422	573	7
	1	4.9	42	15	0.5	43	318	2371	575	9
	2	5.1	62	16	0.4	34	318	2565	596	7
	4.5	5.2	61	14	1.0	42	353	2845	628	11
	9	5.4	88	14	1.7	46	350	3002	662	10
145	0	4.8	35	17	0.5	38	256	2272	543	8
	1	4.9	46	19	0.3	33	307	2506	597	9
	2	5.0	51	17	0.6	49	326	2455	578	9
	4.5	5.0	59	15	1.2	46	336	2519	580	10
	9	5.3	77	14	1.2	36	302	2753	621	10
Analysis of Variance										
N Effect	*P*-value	NS	<0.1	<0.1	NS	NS	<0.1	NS	NS	NS
Si Effect	*P*-value	<0.01	<0.001	NS	<0.001	NS	NS	<0.01	<0.1	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	<0.1	NS	NS	NS	NS

Table C.4. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH and Mehlich-3 extractable micronutrients and metals, NERS 2014, midseason soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Micronutrients and Metals, mg kg^{-1}								
			Cu	Fe	Mn	Ni	Zn	Se	Al	Pb	B
0	0	4.9	3.3	484	136	4.5	3.5	0.14	744	3.0	1.5
0	0+lime	5.3	4.0	479	113	4.8	3.6	0.14	776	3.0	1.1
101	0	4.9	3.6	503	121	4.8	3.5	0.17	802	2.9	1.0
	1	4.9	3.5	509	134	4.4	3.4	0.16	797	3.0	1.6
	2	5.1	3.8	479	127	4.7	3.6	0.15	796	2.8	0.6
	4.5	5.2	3.7	483	107	4.3	3.8	0.17	839	2.9	0.3
	9	5.4	3.9	489	100	4.3	4.4	0.18	850	3.1	0.6
145	0	4.8	3.4	459	117	4.4	3.1	0.19	759	3.0	0.4
	1	4.9	3.8	475	128	5.0	3.5	0.16	801	3.0	0.3
	2	5.0	3.5	519	122	4.8	3.7	0.19	852	3.1	1.1
	4.5	5.0	3.5	490	109	4.5	3.6	0.16	823	2.9	1.2
	9	5.3	3.8	457	115	4.7	3.9	0.19	818	3.3	0.3
Analysis of Variance											
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.05	NS	NS	<0.05	NS	<0.05	NS	NS	NS	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table C.5. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH, 0.5 M acetic acid extractable-Si, soil NH_4^+ and NO_3^-, and Mehlich-3 extractable macronutrients, BH 2014, midseason soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Silicon and Macronutrients, mg kg^{-1}							
			Si	NH_4	NO_3	P	K	Ca	Mg	S
0	0	5.8	23	8	0.6	73	161	1743	310	7
0	0+lime	6.2	38	11	0.6	81	176	2033	326	6
101	0	5.6	30	11	0.4	72	150	1737	304	4
	1	5.9	38	13	0.5	67	148	1893	327	6
	2	5.9	38	10	0.7	71	145	1909	339	5
	4.5	6.2	51	12	1.0	73	144	2007	347	6
	9	6.5	91	12	1.3	73	135	2260	386	9
145	0	5.6	22	13	0.2	67	136	1756	299	5
	1	5.9	34	11	0.5	68	141	1857	315	4
	2	5.9	43	11	0.7	67	141	1910	339	6
	4.5	6.2	55	12	0.9	69	134	2022	347	6
	9	6.4	77	13	1.2	74	147	2261	389	8
Analysis of Variance										
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.001	<0.001	NS	<0.01	NS	NS	<0.001	<0.001	<0.001
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table C.6. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH and Mehlich-3 extractable micronutrients and metals, BH 2014, midseason soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Micronutrients and Metals, mg kg^{-1}							
			Cu	Fe	Mn	Ni	Zn	Se	Al	Pb
0	0	5.8	1.8	506	58	2.3	1.5	0.16	654	3.6
0	0+lime	6.2	1.9	496	59	2.1	1.5	0.20	618	3.6
101	0	5.6	1.8	512	66	2.4	1.5	0.21	627	3.6
	1	5.9	1.9	472	64	2.5	1.7	0.17	610	3.6
	2	5.9	1.9	502	65	2.1	1.8	0.18	660	3.5
	4.5	6.2	1.9	502	68	2.3	1.8	0.18	658	3.6
	9	6.5	2.0	472	67	2.0	2.3	0.17	662	3.5
145	0	5.6	1.8	472	63	2.2	1.5	0.17	613	3.7
	1	5.9	1.9	486	68	2.1	1.8	0.16	627	3.5
	2	5.9	1.9	509	65	2.6	1.7	0.20	682	3.6
	4.5	6.2	1.9	469	65	2.0	1.9	0.21	643	3.8
	9	6.4	2.1	489	70	2.6	2.1	0.14	678	3.7
Analysis of Variance										
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.001	<0.01	NS	NS	NS	<0.001	<0.1	<0.05	NS
N x Si Effect	*P*-value	NS	<0.1	NS	NS	NS	NS	NS	NS	NS

Appendix D. Extractable Nutrients and pH of Harvest Soil Samples

Table D.1. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH, 0.5 M acetic acid extractable-Si, soil NH_4+ and NO_3-, and Mehlich-3 extractable macronutrients, NERS 2013, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Silicon and Macronutrients, mg kg^{-1}							
			Si	NH_4	NO_3	P	K	Ca	Mg	S
0	0	5.6	68	9.9	2.6	38	293	2002	494	8
0	0+lime	6.4	87	9.9	3.6	34	280	2359	515	9
101	0	5.7	62	9.8	2.9	31	268	1968	492	8
	1	5.7	60	9.6	3.5	33	284	2079	516	8
	2	6	83	9.8	3.3	31	260	2124	516	8
	4.5	6.3	118	10.2	4.8	35	294	2472	568	10
	9	6.5	138	10.5	4.9	37	266	2447	552	12
145	0	5.4	58	9.7	3.3	35	278	1987	479	8
	1	5.6	64	10.2	4.3	39	280	2070	494	9
	2	6	78	9.0	4.1	35	279	2242	542	9
	4.5	6.2	118	10.0	4.7	38	293	2343	537	9
	9	7	144	10.5	7.6	36	282	2645	592	11
Analysis of Variance										
N Effect	*P*-value	NS	NS	NS	<0.05	<0.1	NS	NS	NS	NS
Si Effect	*P*-value	<0.001	<0.001	NS	<0.001	NS	NS	<0.001	<0.001	<0.01
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table D.2. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH and Mehlich-3 extractable micronutrients and metals, NERS 2013, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Micronutrients and Metals, mg kg^{-1}									
			Cu	Fe	Mn	Ni	Zn	Al	Cr	Pb	Cd	Co
0	0	5.6	2.33	376	127	2.9	2.8	686	0.06	2.3	0.20	1.3
0	0+lime	6.4	2.27	316	123	2.5	2.9	580	0.06	2.2	0.18	1.3
101	0	5.7	2.21	336	128	2.8	2.7	621	0.06	2.1	0.18	1.3
	1	5.7	2.31	354	127	2.7	2.7	663	0.08	2.2	0.19	1.3
	2	6	2.29	334	126	2.6	3.0	636	0.11	2.2	0.18	1.2
	4.5	6.3	2.49	331	119	2.6	3.4	689	0.18	2.2	0.19	1.2
	9	6.5	2.36	345	117	2.5	3.2	690	0.2	2.2	0.17	1.2
145	0	5.4	2.36	389	116	2.8	2.9	698	0.07	2.2	0.19	1.2
	1	5.6	2.3	375	122	2.9	3.0	677	0.09	2.2	0.20	1.2
	2	6	2.46	351	126	2.8	3.2	690	0.13	2.3	0.19	1.3
	4.5	6.2	2.43	350	127	2.8	3.1	704	0.18	2.2	0.19	1.3
	9	7	2.51	315	121	2.6	3.1	690	0.22	2.2	0.19	1.2
Analysis of Variance												
N Effect	*P*-value	NS	NS	<0.1	NS	NS	NS	<0.05	NS	NS	<0.1	NS
Si Effect	*P*-value	<0.001	NS	<0.1	NS	NS	<0.05	NS	<0.001	NS	NS	<0.05
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table D.3. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH, 0.5 M acetic acid extractable-Si, soil NH_4^+ and NO_3^-, and Mehlich-3 extractable macronutrients, NERS 2014, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Silicon and Macronutrients, mg kg^{-1}							
			Si	NH_4	NO_3	P	K	Ca	Mg	S
0	0	5.1	36	15.3	1.3	62	356	2422	603	9
0	0+lime	5.7	62	14.2	2.2	63	367	3107	668	9
101	0	4.9	39	15.5	2.8	64	383	2616	630	9
	1	5	51	14.2	2.0	59	337	2493	614	11
	2	5.2	60	14.7	3.0	55	347	2774	661	9
	4.5	5.1	58	15	3.7	66	373	2854	666	10
	9	5.4	93	15.2	3.9	69	378	3132	710	12
145	0	4.8	40	14.3	2.1	56	328	2511	609	9
	1	4.9	49	15.4	3.6	54	327	2576	632	10
	2	4.9	52	15.7	3.6	62	341	2675	636	10
	4.5	5	60	16.8	4.7	71	372	2751	651	12
	9	5.5	82	14.7	3.8	59	331	2988	688	11
Analysis of Variance										
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.01	<0.001	NS	<0.05	NS	NS	<0.01	<0.1	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

Table D.4. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH and Mehlich-3 extractable micronutrients and metals, NERS 2014, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Micronutrients and Metals, mg kg^{-1}							
			Cu	Fe	Mn	Ni	Zn	Se	Al	Pb
0	0	5.1	3.4	542	128	5.1	3.4	0.2	831	3.4
0	0+lime	5.7	3.8	514	108	4.9	3.9	0.3	811	3.5
101	0	4.9	3.6	552	113	5.1	3.6	0.3	848	3.7
	1	5.0	3.5	535	133	5.2	3.6	0.3	828	3.6
	2	5.2	3.8	505	116	4.9	3.8	0.3	798	3.5
	4.5	5.1	3.7	530	109	4.9	4.0	0.2	860	3.6
	9	5.4	3.9	530	107	4.7	4.6	0.3	887	3.6
145	0	4.8	3.6	528	119	5.2	3.3	0.3	844	3.5
	1	4.9	3.6	512	121	5.0	3.4	0.3	831	3.5
	2	4.9	3.6	530	115	5.0	3.6	0.3	853	3.5
	4.5	5.0	3.6	524	109	5.0	4.0	0.2	861	3.6
	9	5.5	3.7	501	111	4.5	4.1	0.2	865	3.5
Analysis of Variance										
N Effect	*P*-value	NS	NS	NS	NS	<0.01	NS	NS	NS	NS
Si Effect	*P*-value	<0.01	NS	NS	NS	NS	<0.01	<0.1	NS	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]Chromium was not analyzed for 2014 sites.

Table D.5. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH, 0.5 M acetic acid extractable-Si, soil NH_4^+ and NO_3^-, and Mehlich-3 extractable macronutrients, BH 2014, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Silicon and Macronutrients, mg kg^{-1}							
			Si	NH_4	NO_3	P	K	Ca	Mg	S
0	0	5.6	17	8	1.0	73	171	1713	306	7
0	0+lime	6.1	35	6	1.8	79	173	2043	333	7
101	0	5.6	29	7	0.6	70	155	1743	306	5
	1	5.9	27	6	1.0	68	153	1856	322	6
	2	5.9	30	7	1.0	66	146	1864	328	6
	4.5	6.2	38	7	1.1	72	151	1980	348	7
	9	6.5	56	7	1.3	73	147	2254	383	9
145	0	5.6	30	7	0.8	69	151	1771	308	5
	1	5.9	27	7	0.9	66	156	1909	323	6
	2	5.8	30	7	1.2	69	153	1862	335	6
	4.5	5.9	45	7	1.3	69	155	2082	357	8
	9	6.5	95	8	1.8	72	153	2215	385	9
Analysis of Variance										
N Effect	*P*-value	NS	<0.1	<0.1	<0.05	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.01	<.0001	NS	<0.01	NS	NS	<0.001	<0.001	<0.001
N x Si Effect	*P*-value	NS	<0.1	NS	NS	NS	NS	NS	NS	NS

Table D.6. Effect of varying rates of $CaSiO_3$ slag at sufficient and high N application rates on soil pH and Mehlich-3 extractable micronutrients and metals, BH 2014, harvest soil.

N kg ha^{-1}	$CaSiO_3$ Mt ha^{-1}	Soil pH	Extractable Micro-Nutrients and Metals, mg kg^{-1}							
			Cu	Fe	Mn	Ni	Zn	Se	Al	Pb
0	0	5.6	1.8	515	54	2.0	1.7	0.2	673	3.7
0	0+lime	6.1	1.9	499	57	2.0	1.4	0.2	636	3.9
101	0	5.6	1.9	529	64	2.1	1.4	0.2	649	3.8
	1	5.9	1.9	502	63	2.3	1.5	0.2	657	3.9
	2	5.9	1.8	496	65	2.0	1.5	0.2	661	3.2
	4.5	6.2	1.9	511	68	2.2	1.8	0.2	671	3.9
	9	6.5	1.9	505	72	2.0	2.0	0.2	719	4.0
145	0	5.6	1.8	519	63	2.1	1.5	0.2	707	3.6
	1	5.9	2.0	465	64	2.0	1.8	0.2	604	3.8
	2	5.8	1.8	528	70	2.1	1.5	0.2	701	3.7
	4.5	5.9	2.0	500	67	2.2	2.0	0.2	697	3.9
	9	6.5	2.0	503	74	2.1	2.1	0.2	712	3.7
Analysis of Variance										
N Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS
Si Effect	*P*-value	<0.01	<0.1	NS	<0.01	NS	<0.001	NS	<0.05	NS
N x Si Effect	*P*-value	NS	NS	NS	NS	NS	NS	NS	NS	NS

[1]Chromium was not analyzed for 2014 sites.

Vita

Brandon Ellis White was born in Orlando, Florida in March of 1988. He attended Florida A&M University and received his Bachelor of Science in Landscape Design and Management in December of 2011. After graduating he took a year off from his studies to work and was later accepted in to the School of Plant, Environmental, and Soil Sciences at LSU in January of 2013. Since then, he has worked under the guidance of Dr. Brenda Tubana on N and Si fertilization rates in wheat production in Louisiana. He and his wife, Lanie, married in the summer of 2013.