Using Si-rich materials for increasing fodder grass quality and quantity

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Abstract. Improvement of forage quality is one of the essential issues to enhance livestock productivity. Bahiagrass is a popular fodder plant used as pasture species and for hay production, but it lacks the nutritional quality. In greenhouse experiment, the effect of silicon (Si) (calcium silicate and amorphous silicon dioxide) and nitrogen (ammonium nitrate) supplementation on bahiagrass growth and protein content was evaluated. Both types of fertilizers significantly increased the biomass and crude protein content in leaves of bahiagrass. Higher effect was obtained when Si was applied together with nitrogen. The increases were 78 to 100% for biomass and 57 to 59% for crude protein content. Considering that improved plant Si nutrition mitigates the negative effects of biotic and abiotic stresses, the Si involvement into fertilizer management strategy in fodder crops could be efficient for maintaining productivity and quality.

1. Introduction
The supply of proteins in feed for monogastric animals (i.e. poultry and pigs) is one of the major challenges in animal husbandry [1]. Alfalfa, barley, clover, grass, corn are among fodder crops cultivated primarily for animal feed. Bahiagrass (Paspalum notatum Fluggé) is the most common and widely grown warm-season perennial grass used for grazing and hay production in many regions of our planet [2; 3]. This kind of grass is low in proteins to meet the nutrient needs of livestock. So, increasing the plant N content is critical for improving the nutritive value of bahiagrass.

Many grasses, including bahiagrass, are high accumulators of silicon (Si), sometimes containing up to 10% of dry weight, more than N, P, K and other macronutrients [4]. Silicon is considered as a non-essential element, but it plays an active role in plant development. Silicon promotes the growth of many plant species, particularly among the grasses, providing increases in biomass by up to 70-85%, plant height, weight and surface area of roots, leaf area, and others [5]. Hundreds of studies have shown that Si application can enhance plant resistance to insect herbivores, arthropods, fungal diseases and other types of stresses [6; 7; 8].

Plant supplementation with Si affects the uptake and transport of macro- and micronutrients. Si increases the plant tolerance to heavy metal toxicity [9] and alleviates the symptoms associated with deficiency of some essential nutrients [10; 11]. For example, Si fertilization was shown to improve
plant P nutrition via replacing the phosphate anion from slightly soluble phosphates of Ca, Mg, Al and Fe with the formation of the corresponding silicates [12; 13]. Silicon fertilization was reported to contribute to the regulation of N uptake as well. In the soils extremely high in plant-available N, the application of Si fertilizer reduced the content of N in the aboveground parts of plants [14; 15], while in the N-deficient soils, the supplementation with Si resulted in increasing N and crude protein [16; 17]. Silicon-mediated nitrate transporter gene expression was observed in Si-treated rape plants [14]. It is important that the concentration of Si in wheat straw decreased with increasing N supply [18]. The Si-N interactions in plants remain very poorly understood.

The aim of the current study was to determine the effect of Si-rich substances on the bahiagrass growth and quality as fodder crop.

2. Materials and Methods
In greenhouse experiment, bahiagrass (Paspalum notatum Fluggé) cv Argentine was grown in 1 L plastic pots filled with Grey Forest Soil. Soil chemical properties are presented in Table 1.

The scheme of experiment was the following:
1) Control;
2) N;
3) CaSiO₃ 5 t ha⁻¹;
4) N + CaSiO₃ 5 t ha⁻¹;
5) SiO₂ 5 t ha⁻¹;
6) N + SiO₂ 5 t ha⁻¹.

Silicon materials – calcium silicate slag (CaSiO₃) and amorphous silicon dioxide (SiO₂) - were applied to soil before planting. Calcium silicate slag was obtained from the Kosogorsky Metallurgical Enterprise (Tula region, Russia). It was mostly comprised of CaSiO₃. Inorganic pollutants, including heavy metals, were not detected. Amorphous silicon dioxide (Aerosil A-300) (Ltd Silica, Russia) is a chemically pure substance containing 99.8% of SiO₂. The water-soluble Si was 4.6 ± 0.5 and 48.5± 1.5 mg kg⁻¹, accordingly in CaSiO₃ and SiO₂. Nitrogen as NH₄NO₃ was applied at a rate of 150 kg ha⁻¹ N, which was equal to 0.15 g pot⁻¹.

Table 1. Selected properties of experimental soil.

|                | pH  | Total C, g kg⁻¹ | CEC cmol(+) kg⁻¹ | Total nitrogen, g kg⁻¹ | Total phosphorus, g kg⁻¹ | Total potassium, g kg⁻¹ |
|----------------|-----|-----------------|------------------|------------------------|-------------------------|-------------------------|
| Grey Forest Soil| 7.2 | 24.7            | 12.8             | 3.08                   | 0.91                    | 22.3                    |

Twenty (20) seeds, pre-soaked in distilled water for 24 h, were planted in each pot. The air temperature in the chamber was kept at 26 ± 2°C during the day time and 20 ± 2°C during the night. The light period was 12 h; the light intensity was 150 µmol photons m⁻² s⁻¹. The relative air humidity was 75 ± 5% during the day and 70 ± 5% during the night.

After 4 weeks, plants were harvested and separated into shoots (leaves+stems) and roots. Roots were washed with tap water and then with distilled water. Plant material was dried at 70°C, weighed and ground. The leaf N was analyzed using the micro-Kjeldahl method and crude protein was estimated by multiplying the N concentration by 6.25 [2]. Total Si in roots and shoots was measured after NaOH-H₂O₂ microwave digestion by molybdenum blue colorimetric method [19].

The soil plant-available Si was evaluated using water- and acid-extraction methods. The watersoluble Si was analyzed in fresh soil samples using the following procedure: 1) after removing plant roots, 6.0±0.1 g of fresh soil was placed into a 100-mL plastic vessel; 2) 30-mL of water was added to each vessel; 3) after 1 h shaking, a sample was filtered and a clean solution was analyzed for monosilicic acid by molybdenum blue colorimetric method [19]. This is actual form of plant-available Si present in soil [20]. Another part of soil sample was dried at 65°C for 24 h, ground and sieved
through a 1 mm sieve. Two (2.0±0.1) g of dried soil sample was placed in a 100 mL polyethylene cup. Twenty mL of 0.1 M HCl was added and the mixture was agitated at 200 rpm for 30 min. After standing overnight, the mixture was agitated again for 30 min, then the supernatant was centrifuged at 7000 rpm for 15 min. Si was analyzed in cleaned solution by the above mentioned method.

Each treatment and each analysis were conducted in 4 replications. All data obtained was subjected to a statistical analysis based on comparative methods using Duncan’s multiple range tests for mean separation at the 5% level of significance [21].

3. Results and Discussion

The biomass of the shoots and roots of bahiagrass is presented in Table 2. Applied to soil NH$_4$NO$_3$ mostly had a positive effect on the shoot biomass, providing an increase by 50%, while the Si-rich substances had a higher effect on the root biomass (increases by 40 and 60% for CaSiO$_3$ and SiO$_2$, respectively). The combined application of N and Si had the best positive effect on the roots and aboveground parts of bahiagrass.

| Treatment                  | Dry weight, g plant$^{-1}$ | % relative to control |
|----------------------------|-----------------------------|-----------------------|
|                           | Shoots  | Roots | Shoots | Roots |
| Control                   | 0.14    | 0.05  | 100    | 100   |
| N                         | 0.21    | 0.06  | 150.0  | 120.0 |
| CaSiO$_3$ 5 t ha$^{-1}$   | 0.18    | 0.07  | 128.6  | 140.0 |
| N + CaSiO$_3$ 5 t ha$^{-1}$| 0.25  | 0.09  | 178.6  | 180.0 |
| SiO$_2$ 5 t ha$^{-1}$     | 0.20    | 0.08  | 142.9  | 160.0 |
| N + SiO$_2$ 5 t ha$^{-1}$ | 0.28    | 0.11  | 200.0  | 220.0 |
| LSD$_{0.05}$              | 0.02    | 0.01  |        |       |

The total Si in the roots and shoots and crude protein in the leaves are presented in Table 3. With application of NH$_4$NO$_3$, total Si reduced by 9 and 15% in the roots and shoots, respectively. This fact can be related with low supply of plant-available Si in the soil (Table 4) and rapidly increasing plant biomass under N fertilization. As a result, plants experienced Si limitation. The supplementation with Si led to increasing crude protein in the leaves by 12.1 and 14.5% for CaSiO$_3$ and SiO$_2$, respectively, probably due to the activation of the soil microbial society, including N-fixing bacteria [22]. Another underlying mechanism can be attributed to Si-promoted development of the root system. Higher increases in crude protein (by 57.3 and 59.7%) were observed under combined application of Si and N.

| Treatment                  | Total Si, % | Crude protein |
|----------------------------|-------------|---------------|
|                           | Leaves      | Roots | Leaves | % relative to control |
| Control                   | 0.96        | 1.04  | 7.75   | 100   |
| N                         | 0.82        | 0.95  | 11.62  | 150.0 |
| CaSiO$_3$ 5 t ha$^{-1}$   | 1.05        | 1.23  | 8.68   | 112.1 |
| N + CaSiO$_3$ 5 t ha$^{-1}$| 1.02  | 1.21  | 12.18  | 157.3 |
| SiO$_2$ 5 t ha$^{-1}$     | 1.13        | 1.28  | 8.87   | 114.5 |
| N + SiO$_2$ 5 t ha$^{-1}$ | 1.10        | 1.22  | 12.37  | 159.7 |
| LSD$_{0.05}$              | 0.03        | 0.04  | 0.12   |       |

The soil plant-available Si (water- and acid-extractable) is presented in Table 4. According to the soil classification on Si deficiency, the original soil was classified as highly deficient in plant-available
Si [20]. The addition of N slightly reduced water- and acid-extractable Si forms in the soil. The application of both Si materials significantly increased the plant-available Si, with a greater effect of SiO₂.

Table 4. Content of water- and acid-extractable Si in soil, mg kg⁻¹.

| Treatment            | Water-extractable Si | Acid-extractable Si |
|----------------------|----------------------|---------------------|
| Control              | 4.8                  | 215                 |
| N                    | 4.5                  | 204                 |
| CaSiO₃ 5 t ha⁻¹      | 12.5                 | 245                 |
| N + CaSiO₃ 5 t ha⁻¹  | 14.5                 | 240                 |
| SiO₂ 5 t ha⁻¹        | 15.6                 | 258                 |
| N + SiO₂ 5 t ha⁻¹    | 15.8                 | 257                 |
| LSD₀₅                | 0.3                  | 18                  |

The obtained data has demonstrated that N and Si application significantly increased the biomass and crude protein content in bahiagrass. The application of traditional N fertilizers is a routine tool to improve the fodder grass growth and quality. However, N fertilization can increase disease risk and severity in higher plants [23]. On the contrary, Si is known to effectively suppress multiple diseases in cultivated crops [24]. Silicon-mediated benefits also include enhancing the plant tolerance to numerous abiotic stresses, such as pollutant toxicity, drought, salinity, and others; increasing biomass and volume of roots; increasing the stability of chlorophyll, mitochondria and other plant organelles; improving soil fertility level and availability of macro- and micronutrients and many others that provide systematic improvement of the whole soil-plant system. The combined Si and N fertilization could be promising for maintaining high productivity and sustainability in fodder cultivation.

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