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Short-Term Impact of Elemental Sulfur on Cranberry Nutrition and Crop Performance

Reza Jamaly[1,2*], Serge-Étienne Parent[1], Noura Ziadi[3], Léon E. Parent[1]

[1]Department of Soils and Agri-Food Engineering, Université Laval, Québec City, Canada
[2]Ottawa Research and Development Centre, Ottawa, Canada
[3]Quebec Research and Development Centre, Québec City, Canada
Email: *reza.jamaly.1@ulaval.ca

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Abstract

Cranberry (*Vaccinium macrocarpon Ait.*) is an ammophilous plant grown on acid soils (pH 4.0 - 5.5). Elemental sulfur is commonly applied at a recommended rate of 1120 kg S ha^{-1} per pH unit to acidify cranberry soils, potentially impacting the plant mineral nutrition. The general recommendation may not fit all conditions encountered in the field. Our objective was to develop an equation to predict the sulfur requirement to reach pH_{water} of 4.2 to tackle nitrification in acidic cranberry soils varying in initial pH values, and to measure the effect of elemental sulfur on the mineral nutrition and the performance of cranberry crops. A 3-yr experiment was designed to test the effect of elemental sulfur on soil and tissue tests and on berry yield and quality. Four S treatments (0, 250, 500 and 1000 kg S ha^{-1}) were established on three duplicated sites during two consecutive years. We ran soil, foliar tissue, berry tissue tests, and measured berry yield, size, anthocyanin content (TAcy), Brix, and firmness. Nutrients were expressed as centered log ratios to reflect nutrient interactions. Results were analyzed using a mixed model. Soil Ca decreased while soil Mn and S increased significantly ($p \le 0.05$). Sulfur showed no significant effects on nutrient balances in uprights. The S impacted negatively berry B balance, and positively berry Mn and S balances. A linear regression model relating pH change to S dosage and elapsed time (R^2 = 0.53) showed that to reach pH_{water} of 4.2 two years after S application, 250 - 1000 kg S ha^{-1} could be applied depending on initial soil pH value. The stratification of surface-applied elemental S in the soil profile should be further examined in relation to plant rooting and nutrient leaching.

Keywords

Sulfur, Berry Yield and Quality, Compositional Data, Local Diagnosis, Plant Nutrition, Soil Acidification

1. Introduction

Cranberry is an ammophilous plant [1] grown commercially on acid sandy soils. The recommended pH_{water} range to grow cranberry is broadly defined as between 4.0 and 5.5 [2]. Nitrification is inhibited at $pH_{water} \le 4.2$, curbing the growth of nitrophilous weeds [3]. Ammonium sulfate contributes to soil acidification following ammonium transformation into nitrate [4].

Elemental sulfur (S) is commonly used as an amendment to reduce soil pH [5]. However, the recommended rate of 1120 kg S ha^{-1} to decrease soil pH by one unit [6] [7] [8] may not fit all conditions. Because soil acidity varies widely among production sites and pH is a logarithmic transformation, sulfur application rates should be site-specific. The oxidation rate of elemental S in soils also depends on granule size, composition, application method, contact with S-oxidizing bacteria, the availability of organic substrates, and previous S applications [9] [10].

Temperature regulates the biological transformations of ammonium and elemental sulfur [3]. Elemental S mitigates pest propagation and the severity of fungal diseases through pH change [11]. Change in soil pH also impacts the availability of nutrients in cranberry agroecosystems [12], hence, nutrient balances in soils and plants, and crop performance.

The results of soil and tissue tests can be log-ratio transformed [13] to reflect the ever-changing nutrient relationships [14], partial replacement [15], dilution [16] or crosstalks [17], and allow conducting statistical analyses unbiasedly [18]. When computed from raw concentration data, the standard deviation has little statistical value because components of soil and tissue tests are intrinsically inter-related [18]. The centered log ratio (clr) or multi-ratio is statistically appropriate to diagnose the soil and tissue nutrient status in real space [13].

We hypothesized that elemental S decreases soil pH linearly with dosage and reaction time in cranberry acid sandy soils, and this impacts the results of soil tests, tissue tests, and cranberry yield and quality. Our objective was to develop an equation to predict the S requirement in cranberry soils showing differential initial pH values to reach the pH_{water} of 4.2, and to measure the effect of elemental S on the mineral nutrition and the performance of cranberry crops.

2. Material and Methods

2.1. Experimental Design

This study was initiated in spring 2016 and ended in spring 2018 in Quebec, Canada (46˚14'16" to 46˚19'41.4" N, 72˚02'13.4" to 71˚44'19.7"W), at three sites as follows: 1) Notre-Dame-de-Lourdes (conventional site 9), 2) St-Louis-de-Blandford (organic site A9), and 3) Laurierville (conventional site 10). Sites 9, A9 and 10 were 21, 12, or 9 years old, respectively. The cultivar was "Stevens". Sites Soil series were Saint-Jude (sandy, mixed, acid, mesic Aquic Haplorthod) at site A9, Saint-Samuel (sandy, mixed, acid, mesic Typic Humaquept) at site 10, and Sainte-Sophie (sandy over loamy, mixed, acid, mesic Typic Haplorthod) at site 9.

Permanent plots of 4 m × 3 m (12 m^2) in size were installed in the cranberry basins. The experimental design was a randomized complete block with two replications and four treatments per site, totaling 24 plots per year. Sulfur was applied annually as granular (260 SGN = 2.8 mm Ø) Tiger 90CR S (90% split-pea-shaped pastilles S regular grade manufactured by Tiger Resources Technology, Calgary, AB, Canada). Tiger 90CR is an S-bentonite product claimed to disperse and degrade rapidly into sulphate throughout the growing season. The S amendment (0-0-0-90) was applied at rates of 0, 250, 500, and 1000 kg S ha^{-1}·$year^{-1}$, within the range suggested in literature [6] [7]. The effect of elemental sulfur was monitored during two consecutive years.

The sites were irrigated to maintain soil matric potential between −3 and −7 kPa [19]. The N dosage was 45 kg N ha^{-1} as ammonium sulfate (21% N) on conventional sites or certified fish emulsions (6-1-1) on the organic site. The P dosage was 15 kg P ha^{-1} as triple superphosphate (0-46-0) or bone meal (0-13-0), respectively. The K dosage was 80 kg K ha^{-1} as potassium sulfate (40% K) or sulfate of K and Mg (18% K and 9% Mg). The Cu and B rates were 2 kg Cu ha^{-1} as Cu sulfate and 1 kg B ha^{-1}. Sulfur and NPK fertilizers were applied at the same time.

2.2. Soil Analyses

From the last week of May to early June 2016, 2017 and 2018, soils were randomly sampled in the root zone (0 - 15 cm) before fertilization. Samples were air-dried at 50˚C for 24 h and screened to less than 2 mm before conducting analyses. Soil texture was measured using the hydrometer method [20]. Soil texture varied slightly among sites (**Figure 1**).

Soil nutrients were extracted using the Mehlich III method [21] and quantified by inductively coupled plasma emission spectroscopy. Organic C was quantified by combustion using the Leco CNS-2000 analyzer (LECO Corp., Joseph, MI). Soil pH was measured in a 1:2 soil-solution (0.01 M $CaCl_2$) volumetric ratio. Soil pH values before sulfur treatments in June 2016 are presented in **Table 1**. The pH_{CaCl2} was converted into pH_{CaCl2} as follows [22]:

$$pH_{water} = 1.0205\, pH_{CaCl2} + 0.2941,\ r^2 = 0.995$$

As a result, pH_{water} of 4.20 would correspond to pH_{CaCl2} of 3.83, indicating need for acidification to tackle nitrification at the three sites.

2.3. Tissue and Fruit Analyses

Two hundred tissue samples of fruit-bearing and non-fruiting uprights were collected in each plot between late August and early September [23]. Tissues were dried at 55˚C in a forced-air oven and ground to less than 1 mm. Samples were analyzed for N using the Leco CNS-2000 analyzer. After digestion in a mixture of nitric and perchloric acids, P, K, Mg, S, Cu, Fe, Mn, Al, and Zn were quantified by plasma emission spectroscopy. The B was quantified by the azomethine-H colorimetric method after tissue calcination.

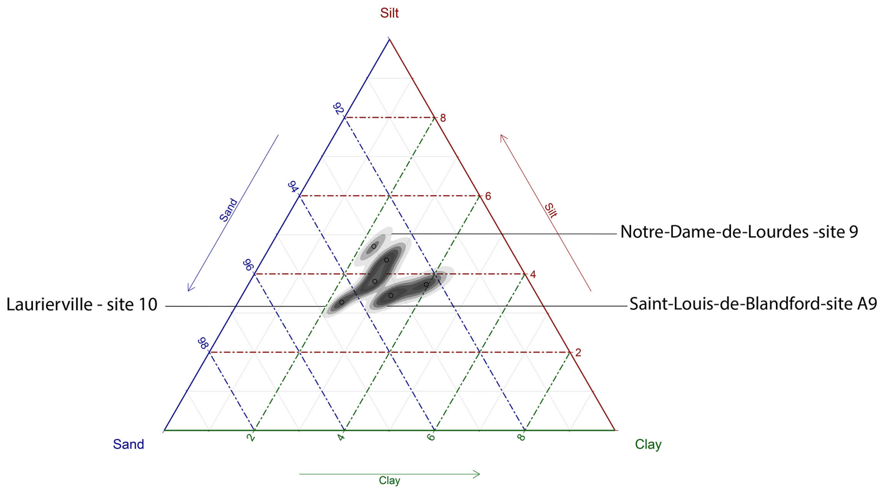

Figure 1. Ternary soil texture plot at experimental sites located on the southern Quebec, Canada.

Table 1. Soil pH as mean and standard deviation (SD) at the onset of the experiment.

Site	Location	pH_{CaCl_2}
10	Laurierville	3.97 ± 0.07
9	Notre Dame-de-Lourdes	4.22 ± 0.14
A9	St-Louis-de-Blandford	4.05 ± 0.05

Fruits were hand-harvested in four 30.5 by 30.5 cm areas per plot before flooding the basins at the beginning of October, then counted and weighed after discarding fruits mechanically bruised, infected by rot, or damaged by insects. Samples were stored at 4˚C after field harvest then frozen at −18˚C for a minimum of 1 month for TAcy and Brix analyses. Berry TAcy (total anthocyanin content) [24] and Brix (refractometer) were analyzed at the Ocean Spray Laboratory of Quality Operating Standard in Warren, WI. Fifty berries for firmness detection were refrigerated per plot overnight and then stored at room temperature for 1 - 2 h. Berry firmness was measured with the TA.TX2 Texture Analyzer (Texture Technologies Inc., Scarsdale, NY) [25]. The trigger force was 0.1 N. Pre-test speed was 1 $mm \cdot sec^{-1}$, test speed, 2 $mm \cdot sec^{-1}$, and post-test speed was 10 $mm \cdot sec^{-1}$. Dried fruit samples (65˚C) were ground to <0.2 mm for mineral analysis. Nitrogen and carbon concentrations were quantified by the Leco CNS-2000 analyzer. The P, K, Mg, Ca, S, Cu, Fe, Mn, Zn, B, and Al were quantified by inductively coupled plasma spectroscopy after nitric acid digestion of 0.2 g dry samples.

2.4. Log-Ratio Transformation of Nutrient Concentrations

Plant nutrients are interrelated and multivariate. Nutrient relationships are commonly expressed as pairwise ratios [26]. Pairwise ratios can be integrated into a single multi-ratio formulation using the centered log ratio transformation (clr) as follows [13].

$$clr_{x_i} = \frac{x_i}{g(x_i)}$$

where x_i is the i^{th} D-part component of tissue composition, and $g(x_i)$ is geometric meanacross components, computed as follows:

$$g(x_i) = \sqrt[13]{\mathrm{C} \times \mathrm{N} \times \mathrm{P} \times \mathrm{K} \times \mathrm{Mg} \times \mathrm{Ca} \times \mathrm{Al} \times \mathrm{S} \times \mathrm{Mn} \times \mathrm{Zn} \times \mathrm{Fe} \times \mathrm{Cu} \times \mathrm{F_v}}$$

Each *clr* expression is a linear combination of pairwise ratios, exemplified by the N balance as follows:

$$clr_N = \ln \frac{N}{g(x_i)} \ln \left(\frac{N^{13}}{\mathrm{C} \times \mathrm{N} \times \mathrm{P} \times \mathrm{K} \times \mathrm{Mg} \times \mathrm{Ca} \times \mathrm{Al} \times \mathrm{S} \times \mathrm{Mn} \times \mathrm{Zn} \times \mathrm{Fe} \times \mathrm{Cu} \times \mathrm{F_v}} \right)^{\frac{1}{13}}$$

where $\mathrm{F_v}$ is the filling value computed by difference between measurement unit and the sum of nutrient concentrations.

2.5. Statistical Analysis and Model Validation

We used the open-source statistical software R [27] version 4.2.2 to analyze the data and draw figures. Soil, upright and berry compositions were clr-transformed to run statistical analysis. Data were standardized to express slope coefficients on a common scale. The R packages were compositions [28] (version 2.0.4) for clr transformations, vegan [29] (version 2.5.7) for ordination, tidyverse [30] (version 1.3.1) for data wrangling, ggtern [31] (version 3.3.5) for soil texture triangle and nlme [32] (version 3.1.155) to compare the coefficients [33]. Significance was tested for each primary outcome at the 95% compatibility interval to avoid converting the p-value into a Bayes factor [34]. Sulfur and year effects were calculated as linear coefficients using a mixed model. Random effect was computed for each site within years and for each block within sites or years. Model accuracy was measured by the R^2 coefficient.

3. Results and Discussion

3.1. Effect of Elemental S on Soil pH

Sulfur dosage impacted soil pH over two years (**Table 2**). The regression model relating pH_{CaCl2} to sulfur *dosage* through years was linear as follows:

$$\text{Final } pH_{CaCl2} - \text{Initial } pH_{CaCl2} = -0.0001586429 \times \mathrm{S}\ dosage - 0.0779807692 \times \Delta year$$

Table 2. Effects of S application on pH_{CaCl2} of cranberry soils.

Treatment	Initial pH_{CaCl2}	Final pH_{CaCl2}
Kg S ha^{-1}	mean ± standard deviation	
S0	4.12 ± 0.20	4.06 ± 0.12
S250	4.09 ± 0.16	3.97 ± 0.03
S500	4.03 ± 0.05	3.86 ± 0.05
S1000	4.08 ± 0.12	3.76 ± 0.08

where $\Delta year$ is elapsed time in year and *dosage* is the annual S application rate (0 to 1000 kg of S ha^{-1}). The R^2 coefficient of the mixed model was 0.53, indicating high variability where sulfur was surface applied in field trials compared to the thorough mixing of elementary S and soils monitored in traditional incubation studies [35]. Indeed, soil acidification rate must vary widely with initial pH, sulfur source and rate, the method of application, soil buffering capacity and the abundance or activity of S oxidizers over time [35] [36] [37] [38].

Two years after S applications, the pH_{water} of 4.2 was reached by applying 250 kg S ha^{-1} at site #10, the most acidic soil condition, 500 kg S ha^{-1} at site #A9 of intermediate soil acidity, and 1000 kg S ha^{-1} at site #9, the less acidic soil (**Figure 2**). In comparison, S dosage up to 1120 kg S ha^{-1} split in two applications has been recommended to decrease soil pH by one unit [6] [7] [8], likely in soils showing much higher initial pH values than in the present study (upper limit recommended for pH_{water} is 5.5) [2]. The vertical distribution of soil pH_{water} values must be highly variable where sulfur is surface applied at the various rates and under various initial soil pH values. The stratification of soil pH over time should be further investigated in relation with plant rooting depth.

3.2. Soil Elemental Composition and Balances

Elemental sulfur tended to increase the S concentration in soils but to decrease that of Ca (**Table 3**). There was a comparable pattern for the clr values reflecting soil S and Ca balances (**Figure 3**). The fact that soil S increased markedly with S additions indicated effective conversion of elemental sulfur into sulfuric acid. The oxidation rate depends on soil moisture, aeration, surface area of S particles, microbial population and the contact between S particle and microbes [39] that are site-specific.

3.3. Effect of Elemental S on Nutrient Levels in Plant Tissues

The S treatments apparently impacted upright nutrient composition more than berry nutrient composition as shown by average values (**Table 4**). The N, S, P, K, Cu and Al concentrations in uprights were highest for the highest S treatment. However, the clr values was shown to increase significantly for the S balance only, to decrease significantly for the Zn nutrient balance only (**Figure 4**).

Table 3. Effects of S application on soil composition.

Treatment	N	S	P	K	Ca	Mg	Cu	Zn	B	Mn	Fe	Al
	mg Mehlich-3 element·kg^{-1} in soil											
S0	871	17	59	21	74	8.0	2.0	1.0	NA	1.4	119	1067
S250	839	24	64	19	56	7.0	1.9	0.8	NA	1.4	125	1124
S500	855	30	61	19	60	7.2	1.9	0.9	NA	1.5	122	1042
S1000	859	42	59	19	47	7.3	2.0	0.9	NA	1.2	129	1015

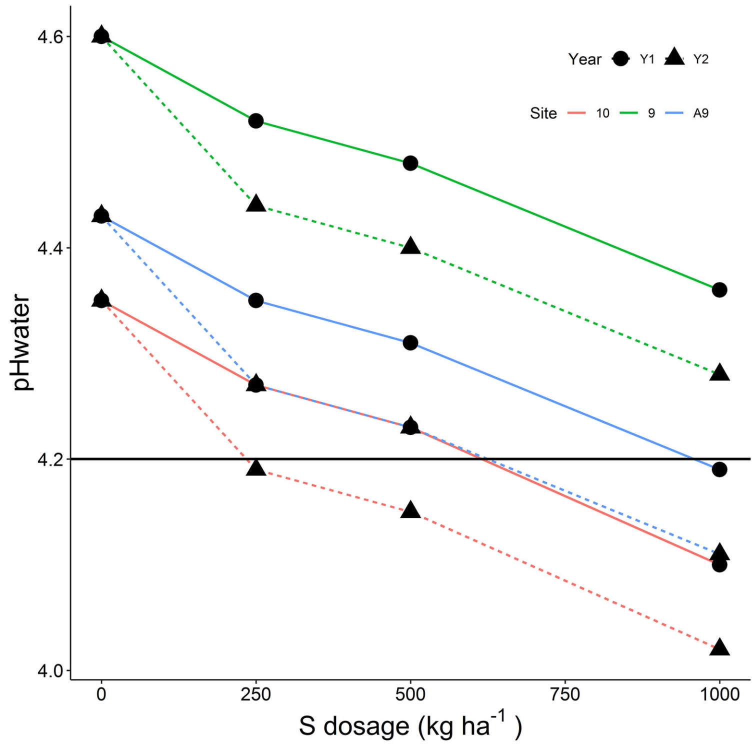

Figure 2. Trends in soil pH_{water} of cranberry soils at experimental sites one year (Y1 as solid lines) or two years (Y2 as dashed lines) following S application to reach pH_{water} of 4.2 at the three sites.

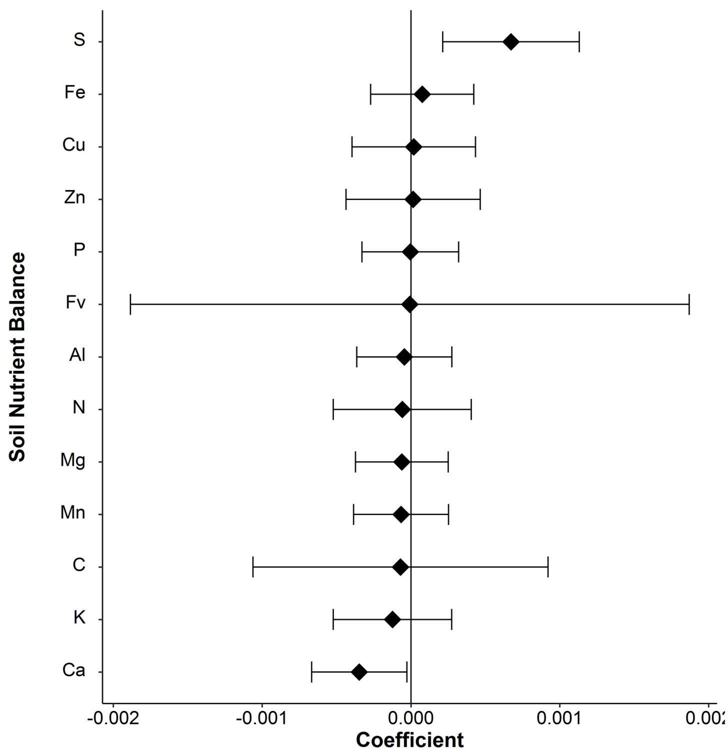

Figure 3. Coefficients of a linear mixed model showing the effect of sulfur on the log of soil nutrient balances.

Table 4. Effects of sulfur treatments on average nutrient concentrations in uprights and berries.

Treatment	N	S	P	K	Ca	Mg	Cu	Zn	B	Mn	Fe	Al
	Uprights											
	g element·kg^{-1}						mg element·kg^{-1}					
S0	7.71	1.32	1.10	6.89	7.25	1.87	4.0	20	97	273	81.5	65
S250	7.75	1.81	1.16	6.68	7.89	2.10	4.0	20	87	372	86.0	82
S500	8.04	2.42	1.13	7.27	6.77	2.04	4.0	19	96	360	84.5	96
S1000	8.82	3.22	1.22	8.23	6.27	2.15	6.5	17	85	352	95.3	128
	Berries											
	g element·kg^{-1}						mg element·kg^{-1}					
S0	3.28	3.84	0.82	5.37	0.60	0.36	4.0	4.5	9.0	11.0	13.5	16.5
S250	3.50	3.99	0.83	4.87	0.59	0.35	4.0	4.0	7.5	12.0	19.0	20.0
S500	3.12	4.21	0.80	5.10	0.58	0.35	4.0	4.5	8.5	15.0	14.5	17.0
S1000	3.43	4.71	0.80	5.33	0.47	0.34	4.0	4.0	8.0	13.5	16.0	19.5

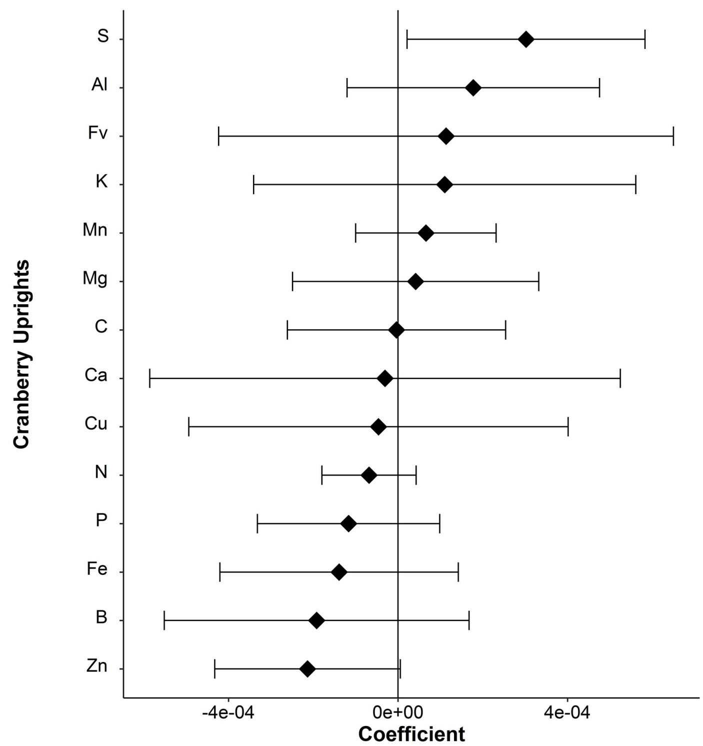

Figure 4. Coefficients of a linear mixed model showing the effect of sulfur on the log of cranberry uprights.

3.4. Effect of Elemental S on Crop Performance and Berry Mineral Composition

Because cranberry grows in strongly acidic soils where aluminum [40], iron [41], and Mn [42] toxicity may occur, the bioavailability of Fe and Al may increase and that of S decrease with the application of elemental sulfur to lower soil pH [6]. The Al toxicity in plant tissues may be problematic in acid soils at pH values lower than 5.5 [40]. Soil pH_{water} below 4.8 may cause Mn toxicity to sensitive crops [43] [44] but this was apparently not a problem for cranberry. The S treatments did not impact significantly fruit Brix, firmness, TAcy, weight and yield (**Figure 5**). Possibly, crosstalks between S, Mn, Fe and Al may tackle metal toxicity [45].

While excessive N inputs may redirect C allocation and produce vegetative overgrowth [46] [47], the nitrogen appeared to be properly balanced with other tissue components to reach high berry yield and quality in the present study. The sulfur increased berry S and Mn, but decreased berry B significantly (**Figure 6**). Indeed, the bioavailability of Fe and Al may increase, but negatively related to berry B by adding elemental sulfur as treatment to lower soil pH [6] [48]. Total B demand depends on berry yield [49] and is also impacted by N additions [50]. Boron nutrition, if not addressed properly, could decrease fruit resistance to diseases [51] [52]. The indirect impact of S amendments on nutrient availability could be addressed in future studies in relation with boron in cell structure and integrity [53].

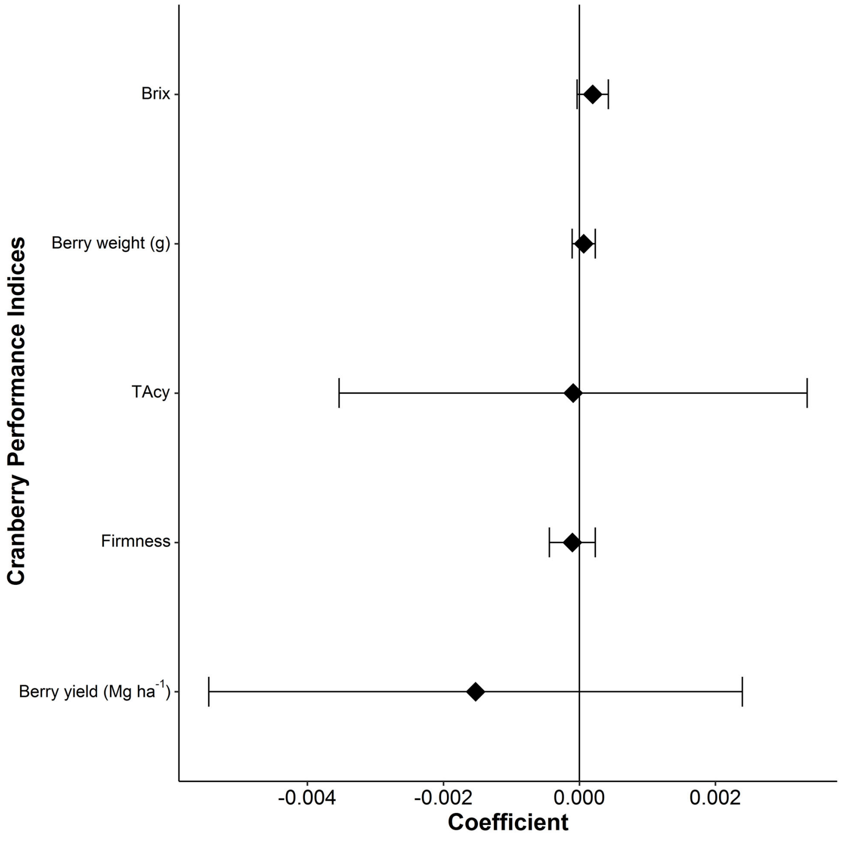

Figure 5. Coefficients of a linear mixed model showing the effect of sulfur on cranberry performance indices.

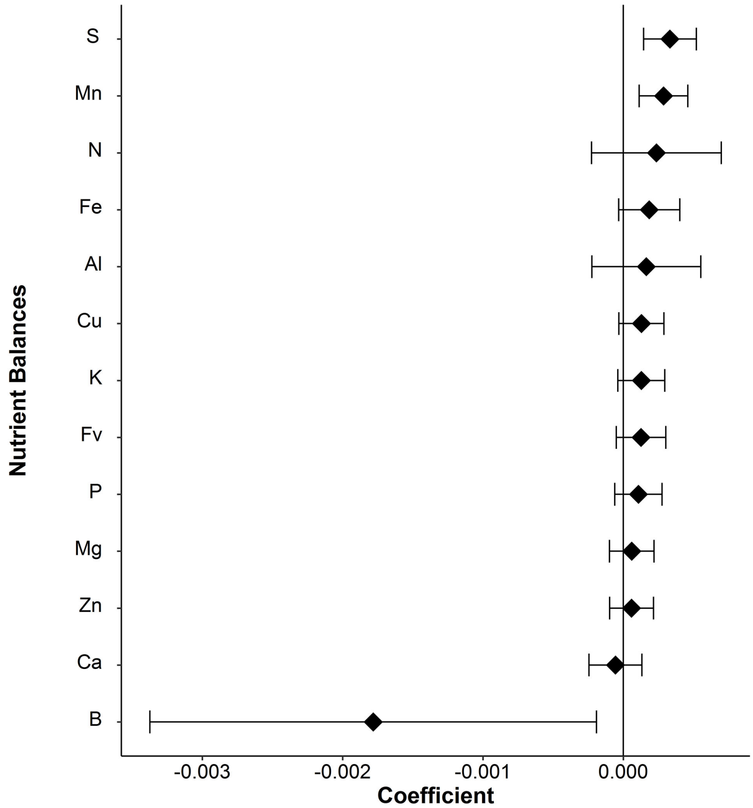

Figure 6. Coefficients of a linear mixed model showing the effect of sulfur on the log of nutrient balances.

4. Conclusion

This study provided an empirical linear equation relating pH change to S dosage and reaction time in cranberry agroecosystems. Elemental S decreased soil pH linearly during a 2-yr period. Depending on initial soil pH, 250 - 1000 kg S ha^{-1} would be necessary to reach pH_{water} of 4.2 to curtail nitrification. Soil Ca and Mn balances expressed as centered log ratios decreased, while soil S balance increased with S dosage. Berry yield and quality indices as well as upright nutrient balances were not affected significantly two years following the S treatments. Berry B balance that may impact fruit quality decreased significantly, while berry Mn and S balances increased significantly. Nutrient interrelationships differed between the cranberry fruit and vegetative tissues. Complementary information derived from both tissue tests could be addressed in future studies to plan fertilization and S management.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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