ASSESSING RESPONSE OF FOUR ECONOMICALLY SIGNIFICANT VEGETABLE CROPS TO GYPSUM AS A SUPPLEMENTAL SULFUR SOURCE IN NEW YORK

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ABSTRACT

Sulfur (S) deposition rates have decreased in the past several decades. In this thesis, we evaluate the response of economically significant vegetable crops English pea (*Pisum sativum*), snap bean (*Phaseolus vulgaris*), sweet corn (*Zea mays*) and tomato (*Solanum lycopersicum L.*) to gypsum. Gypsum was chosen as a supplemental S source because it is cheap, widely available, and is easily inserted into fertility programs. By conducting gypsum fertilizer trials with three economically important processing crops and one fresh market crop, a broad overview was available to answer whether sulfur deficiencies were already a widespread issue in New York vegetable production. Throughout all off our trials and data collected in 2018 and 2019, no statistically significant results were found that gypsum had a positive effect on any of the vegetable crops tested. Thus, we conclude that S is not limiting production of the crops evaluated, on fine textured soils in New York.

BIOGRAPHICAL SKETCH

The author grew up in the city of Geneva, New York, in the United States of America. In 2012, he received his Associates of Arts from Finger Lakes Community College and went on to earn his Bachelor of Philosophy and Environmental Studies in 2015, from Hobart College. During his undergraduate education, Michael worked seasonally at Cornell's AgriTech and ran his own vegetable stand; both activities led to a burning passion for horticulture. After graduating, Michael continued farming in his personal time and worked for a utility company in efforts to save money and attend graduate school. Michael began his graduate studies at Cornell in the Fall of 2017, in Dr. Reiners' variety trials and vegetable processing program, which he currently manages as a Research Support Specialist. Michael currently lives in Geneva, with his wife, Christine Rosato, daughter, Mariana Rosato, and dog, Oakley Rosato. Michael and Christine currently lease land in Phelps, NY where they run a small vegetable farm, and hope to put down their roots.

DEDICATION

I dedicate this project to my late father, Lester William Fillingham, a veteran, fireman, lineman, and dedicated family man. A stepparent and stepchild always encounter extremely awkward situations, you handled them all with grace. When my biological father was crippled from a violent assault, you were with me every step of the way and were the rock I so desperately needed. You always treated me as your own and pushed me to do my best. After being married to my mom for over 22 years, you became more than a father, and I am lost for the words to describe your love and our relationship. I wish I could say thank you a million more times and tell you how much you mean to me. You are the most kind and honorable man I have ever met. I will do my best to carry on your legacy and make you proud. Your name will never be forgotten, and we will speak of “Poppi” often to the kids. Until we meet again, rest in peace.

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CHAPTER 1

Declining Soil Sulfur Levels and Relevance to Vegetable Production: A Review

Introduction:

Soil sulfur (S) deficiencies have become more prevalent across the US with documented deficiencies in the Midwest, Southeast, and Northeast over the past decade (Camberato & Casteel 2017; Johnson 2018; Ketterings et al. 2012). Researchers have recorded S deficiencies in alfalfa (*Medicago sativa*), sweet corn (*Zea mays*), soybean (*Glycine max*), watermelon (*Citrullus lanatus*), tomatoes (*Solanum lycopersicum L.*) and other crops. Historically, S has been sufficient in soils and thus not generally been included in routine soil and tissue testing or fertilizer programs. However, atmospheric deposition of S has declined over the past four decades and synthetic fertilizer is increasingly utilized over manure in vegetable production systems, causing soil S levels to decrease over time (EPA 2019; Rosen & Bierman 2005). As S deficiencies can impact crop yield and quality, it is imperative that researchers evaluate their region's risk for S deficiencies and develop guidance on S management of crops to avoid negative economic consequences.

New York has an impressive agriculture sector producing a $5.75 billion revenue in 2017 (New York Farm Bureau 2019). The vegetable sector in New York was valued at about $379 million in 2017, making New York a competitive vegetable producing state nationwide (Office of Budget and Policy Analysis 2019). Growers in New York produce high quality vegetables for both fresh markets and processing markets. The margin of profit on processing crops is small for both growers and processors, and it is imperative crop yields are increased, or at the very least maintained. Sulfur, a constituent of many proteins and chlorophyll, can have a direct impact on yield, and deficiencies pose an obvious risk to the processing industry. Sulfur can impact quality, such as pungency in crucifers, garlic, and onion (Thangasamy et al. 2013), and protein quality in soybeans (Rushovich & Weil 2021) and could potentially have negative or positive impacts on vegetable flavor (McGorrin 2011), but additional research is needed.

With any relatively uncommon, or emerging nutrient deficiency, it is crucial to review the existing literature on identifying and remedying such deficiencies. Research on S deficiencies has increased in the past decade but is often limited to specific areas and specific crops. It is important to expand our knowledge across all vegetable crops in diverse scenarios. The more different soil types, crops, climates and other factors are accounted for, the better management guidelines can be developed.

Historical Overview of Sulfur:

Fossil fuels, such as coal, crude oil and natural gas, innately contain S in organic and inorganic forms (Mezey et al. 1976). When fossil fuels are combusted, the S is released into the atmosphere as the byproduct sulfur dioxide. Sulfur dioxide in the atmosphere can lead to both health and environmental challenges. For example, high concentrations of atmospheric sulfur dioxide can negatively affect the human respiratory system directly or from other sulfur oxides which do similar damage (EPA 2019). Sulfur dioxide also plays a role in increasing acid rain and negatively impacting ecosystems around the world (EPA 2019). In the US, it was estimated that about 2,000 terawatt-hour (TWh) of fossil fuels were produced in the year 1900, while in 1970, the US produced about 16,500TWh of fossil fuels and consumed about 18,000TWh (Ritchie &

Roser 2019). The substantial increase in production and consumption of fossil fuels was driven by the industrial revolution which allowed the US and other countries to increase production of goods and economic growth. The increased usage of fossil fuels, however, also led to increased levels of sulfur dioxide in the atmosphere.

The consequences of increased sulfur dioxide were first discovered in North America by the Hubbard Brook Ecosystem Study at the Hubbard Brook Experimental Forest, NH, in 1963 (Likens & Bailey 2014). The study was initially created to experiment with using watersheds and chemistry to measure greater ecological functions and health (Likens & Bailey 2014). The first precipitation samples taken for the project recorded a pH of about 3.7 and the first year of samples averaged a pH of about 4.1 (Likens & Bailey 2014). One of the founders of the Hubbard Brook Ecosystem Study, Gene Likens, joined Cornell University in 1969 and set up precipitation collection sites on Cayuga and Seneca lakes (Likens & Bailey 2014). Likens discovered that the precipitation in upstate New York was similarly acidic to his earlier findings at the Hubbard Brook Experimental Forest. Traveling to Sweden in 1969, Likens found that Western European countries were also experiencing acid rain, which researchers attributed to increased sulfur dioxide from industrialized countries (Likens & Bailey 2014). Likens and colleagues published the first paper documenting acid rain and S pollution in North America in 1972 (Likens & Bailey 2014, Likens et al. 1972).

In response to the discovery and cause of acid rain, the US government made attempts at policy change to reduce air pollutants. Early attempts in 1955 and 1967 largely failed (EPA 1990). In 1970, the Environmental Protection Agency (EPA) was created, and one year later, the EPA enacted 36FR8186, which would set the first metrics for the National Ambient Air Quality Standards for sulfur dioxide emissions (EPA 1990). The results of these emissions standards were primarily focused on lowering levels of S in energy sources such as coal and crude oil. In 1990, approximately 23.1 million tons of sulfur dioxide were emitted into the atmosphere in the US (EPA 2018). In 2016, emissions were reduced to about 2.7 million tons of sulfur dioxide, a nearly 90% decrease in that one pollutant (EPA 2018).

The EPA's regulations were a great success for cleaning the air but resulted in decreasing soil S levels, both from decreased atmospheric deposition as well as an evolving agricultural industry. The three-year annual average of total atmospheric S deposition into soils, from 2000 to 2002, in the northeastern US was about 11 kg ha^{-1} (EPA 2019). The latest data from the EPA shows that the northeastern part of the US received about 2.7 kg ha^{-1} annually (EPA 2019). To put the decreasing atmospheric depositions into context, corn grown for silage can remove about 34 kg ha^{-1} and corn grown for grain can remove about 18 kg ha^{-1}, which could lead to a net S deficit when considering decreased atmospheric deposition and the absence of addition of S in the form of fertilizer or manure (Kaiser & Vetsch 2019). If S deposition continues to decline in future years, soil S deficits are highly likely. Although the Clean Air Act, passed in 1970, is a major contributor to declining soil S levels, decreased use of manure and increased use of purer synthetic fertilizers have also played a significant role.

Sulfur has historically been introduced directly to soils from manure applications as well as in byproducts within fertilizers. Depending on the manure source, the S content of manure can range from 0.7 to 1.4 kg per ton of solid manure, or 1.8 to 4.1 kg of S per 1,000 pounds liquid manure (Schulte & Kelling 1992). For farmers growing field corn, an application of about 25 tons of solid manure per acre supplies about 100 to 112 kg N ha^{-1} (Beegle 2017), and among other nutrients, also contains about 28 kg ha^{-1} of S. Many vegetable fertility guidelines, depending on past fertilizer programs and soil organic matter content, call for applications of about 90 to 112 kg ha^{-1} of N (Laboski & Peters 2012). When manure is used to supply this N, it could add anywhere from 11 to 34 kg ha^{-1} of S. In comparison, guidance for S typically calls for 17 to 34 kg ha^{-1} (Camberato & Casteel 2017, Kaiser & Vetsch 2019). Thus, manure has historically been an effective way to add adequate amounts of S to soils.

Before the industrial revolution and automobiles, it was common for farmers to own horses and livestock, as well as run a diversified business that included animals (Kelly 1990). Under these conditions, a farmer would likely have enough manure on site to use for vegetable and field crop production. At the same times machines replaced horses, US farming evolved after World War II resulting in more specialization and less diversification. Once farmers began specifically growing vegetables or crops only, they lost their local manure supply. Logistics as well as cost became a factor in determining the types of fertilizer to use. Issues such as manure hauling, the need for specialized spreading equipment, efficiency of spreading the manure and concentration of nutrients all became factors farmers had to consider when deciding to use manure instead of synthetic fertilizer (Kelly 1990).

Although it is difficult to quantify historical usage of manure, the use of synthetic fertilizers can help fill in the gaps to some extent. In the 1940's, about 2 million tons of synthetic fertilizers were used on farms in the US, compared to about 20 million tons in 2014 (Hergert et al. 2015). The significant increase in synthetic fertilizer usage likely reflected decreased fertilizer costs and increased tillable acres and decreased manure usage (Hergert et al. 2015) and greater awareness of food safety risks (Astill et al. 2019).

At first, growers who switched from manure to synthetic fertilizers did not necessarily eliminate the application of S as several widely used synthetic fertilizers contained S as a byproduct. For example, superphosphate fertilizer, a common phosphate fertilizer in the 20th century, contained S. This fertilizer is manufactured using mined rock phosphate with a potential P_2O_5 content of about 14 to 35% (Vossen n.d.). Unfortunately, in that form and even after being pulverized, rock phosphate is mostly unavailable to plants (Vossen n.d.). To make phosphate more readily available to plants it can be treated with acid, which traditionally has been sulfuric acid. Sulfuric acid is a versatile chemical that is widely used in several industries and historically has been a popular additive in many fertilizers. Superphosphate was an almost ubiquitous source of phosphate in the 20th century and depending on the manufacturer, contained about 12% S (Duncan 2008). If a grower added 45 kg of superphosphate to a field to get 9 kg of P_2O_5, they would be adding about 6 kg of S. As fertilizer production has become more precise and efficient, byproducts such as S have largely been eliminated.

In the US, roughly 900 to 3,000 people are sickened annually from food born illnesses related to fresh produce (1998-2016) (Johnson 2019). Vegetable growers tend to grow crops that are eaten fresh without a kill step such as boiling or steaming, and thus have a higher risk of selling contaminated products. The most common pathogens related to foodborne illness, with regard to fresh produce, are *Norovirus*, *Salmonella*, and *E. coli 0157* (Johnson 2019). Both *Salmonella* and *E. coli 0157* can be easily transferred from raw manure to produce. In an effort to reduce risk of such illnesses, President Obama signed the FDA's Food Safety Modernization Act (FSMA) into law in 2011 (FDA 2018). The FSMA was created to update the US food safety protocols and also change the system from reacting to food safety issues, to proactively focusing on prevention. Currently, in the US, there is no federal regulation that sets a minimum amount of time between applying manure and harvesting. The only rule in place is that "covered" farms, or operations that meet specific FDA metrics such as size and production, must apply manure in a way that does not touch the produce and minimizes the risk of manure touching produce after application (FDA 2018). A proposed prevention measure was to create a mandatory interval between raw manure application and produce harvest. In 2013, the FDA proposed a nine-month interval between application of raw manure and harvest (FDA 2018).

The proposed policy caused pushback from the agricultural industry because it lacked scientific data validating the interval. Growers and environmental groups also pushed back because it made poor logistical sense. For example, if a vegetable grower is focusing on early greens production in upstate NY, they can be harvesting as early as late April. Under the proposed nine-month interval, that grower would have had to apply manure the previous August at the height of the previous years' growing season. This would be impossible if another vegetable crop was growing in that field at that time. Even if the field was in fallow, the grower would have to monitor weather conditions to appropriately apply manure at a time to avoid nitrate leaching. In this environment, a good deal of N could be lost through the winter, creating a major environmental problem. When the long timeline is considered, with the unpredictability of the environment, it becomes apparent why creating a realistic timeline is important for both health reasons and sustainable farming practices. The FDA ultimately decided not to make the nine-month interval the law while further assessing the risk of raw manure in produce production (FDA 2018).

Since that time, the FDA suggests growers follow the USDA's National Organic Program Standards, which calls for a 120-day interval for manure application for crops in contact with the soil and 90 days for crops not in contact with the soil (FDA 2018). Although the proposed nine-month interval has not been signed into law, the new FSMA regulations are creating a tighter food safety culture and will likely make vegetable growers more aware of the risks of using raw manure. In addition, most growers that sell to wholesalers are required to meet the buyers' requirements in terms of manure handling. Due to all these issues, manure usage on vegetable farms across New York has declined, with the possible exception of small-scale, diversified, organic operations. The ease, efficiency and cost of using synthetic fertilizer, mixed with the increasing liability of using raw manure, will likely keep many vegetable farmers using synthetic fertilizers. If the trends of decreased atmospheric deposition of sulfur, less usage of manure and less sulfur additives in synthetic fertilizers continue, it is likely soil sulfur deficiencies will become more common and growers will need to address S in their fertilizer regimes, with the help of extension educators and crop consultants.

Sulfur Nutrition, Deficiencies and Sources:

As sulfur deficiencies become more common throughout the United States and the Northeast, it is important that growers and extension educators recognize both; the role sulfur plays in plant development as well as sulfur deficiency symptoms. Sulfur is considered one of six essential plant macronutrients, but comparatively research is limited, likely due to the assumed abundance in soils. Typically plant roots are responsible for majority of S uptake in the sulfate anion form. Above ground parts of the plants can absorb sulfur dioxide from the atmosphere to a much lesser extent (Marshcner 2012). With the assistance of S transporters (Hawkesford 2003), the sulfate anion travels through the transmembrane barrier and then through the xylem and phloem (Marschner 2012). Sulfur can be utilized in plants in both a reduced and non-reduced form. Sulfur is present in various forms in plants, perhaps most importantly in amino acids cysteine and methionine, as well as glutathione and sulpholipids (Marschner 2012). Cysteine, an amino acid, is the precursor to all organic compounds containing reduced S and therefore an integral part of plant S metabolism (Marschner 2012). Cysteine and methionine are components of various proteins, many of which are located in the chloroplasts and have a direct impact on chlorophyll concentration (Maschner 2012). Sulfur deficient plants exhibit lower levels of cysteine and methionine and in turn less proteins in general. Less protein in the chloroplast results in lower chlorophyll levels and lower rates of photosynthesis, which in turn can result in lower yields, soluble solids, and other negative impacts. Glutathione, a S containing thiol, is a powerful antioxidant that allows plants to detoxify reactive oxygen radicals and helps manage pathogens in plants (Rouhier et al. 2008). Glutathione also plays a vital role in heavy metal detoxification in many plant species and can serve as a S reserve. Glutathione has also been linked to human health benefits. Sulpholipids, a specialized lipid containing S in plants, are found in thylakoid membranes and are thought to be important in photosystem II. Further, sulpholipids seem to be involved in helping plants adapt to environmental stressors such as high salt or cold temperatures (Marschner 2012; Taran et al. 2000). Beyond the compounds and functions listed above, S is diversely used throughout the plant and its metabolism in many ways, and like other essential nutrients it is important to understand symptoms and signs.

Sulfur's role in amino acid and protein synthesis is a major factor when considering visual deficiency symptoms. Plants deficient in sulfur often lack normal amounts of protein and chlorophyll. Insufficient proteins and chlorophyll can result in the yellowing of leaves among other symptoms not easily seen by the naked eye. There is no clear consensus in the literature on S mobility in plants which has a direct impact of diagnosing deficiencies in the field. Most of the literature, especially extension recommendations, claim that S is relatively immobile in plants and therefore symptoms will generally occur in younger leaves (Goldy 2013; McCauley et al. 2009). In contrast, there are also claims that S is indeed mobile or at least intermediately mobile in plants (Wardlaw & Passioura 1976; Marschner 2012). Chlorosis tends to be uniform when S deficiency is responsible but can occur on both mature and young leaves which can cause some confusion. General chlorosis and specifically yellowing of old leaves is a very common and well-known sign of N deficiency. Therefore, diagnosing S deficiency can sometimes be a challenge. The inconsistency of which leaves experience chlorosis may be related to the species of plant and at which point S deficiencies occurred during plant development (Hawkesford & De Kok 2006). When some species of plants experience S deficiencies early on in development it is difficult for the plant to remobilize sulfur from older leaves to younger leaves. Whereas, when plants experience sulfur deficiencies later in development, it seems the plant can remobilize some S from older leaves and translocate to younger leaves (Hawkesford & De Kok 2006). For these reasons, chlorosis due to S deficiencies can appear on both older and younger leaves (Hawkesford & De Kok 2006).

Although S is an essential nutrient for all plants, different cultivars and species seem to vary in S consumption. The Cruciferae family is generally viewed as requiring the most S, removing up to 50 kg ha^{-1} (Schonhof et al. 2006; Marschner 2012; Heckman 2021). Further, the genus Allium requires sulfur for the characteristic pungency of its members such as garlic and onion and is generally thought of as requiring moderate to high levels of soil S compared to other vegetable crops. Most vegetable crops remove anywhere from 5 to 28 kg of S ha^{-1} (Heckman 2021). Generally, tissue samples in the range of 0.1 to 0.5 % S (dry weight basis) signal sufficiency of S for optimum plant growth (Marschner 2012; Heckman 2021).

Unfortunately, there is no strong consensus when it comes to soil S levels relating to sufficient or deficient levels for vegetable crops. Sulfate is similar to nitrate in several ways: it has a negative charge, is easily leached and volatilized, is dynamic and thus can be difficult to accurately test for in soils (Marschner 2012). Further, S is present in organic matter which breaks down over the course of the growing season and is not quantified in soil tests. The general rule of thumb is to assume about 1.4-2.3 kg of S per percent organic matter per growing season (Kaiser & Vetsch 2019).

In recent field crop studies, Cornell researchers analyzed several soil sampling methods and concluded that a 0.01 mol L^{-1} $CaCl_2$ extractable S method was the most accurate test for New York soils (Ketterings et al. 2012). A critical soil test S level of 8 ppm was set for samples taken at 2nd cutting of alfalfa (Ketterings et al. 2012). Currently there is no similar critical threshold for vegetables but given reduced S deposition and limited use of manure for vegetable production research is needed to evaluate if a similar test can be used to identify deficiencies.

Growers have several options when it comes to remedying S deficiencies in soils. As previously mentioned, manure applications in the fall are a quality source of S for the following growing season, adding about 0.7 to 1.4 kg of sulfur per dry ton (Schulte & Kelling 1992). Fall application is crucial to allow microorganisms time to turn unavailable S into the plant available sulfate form. Elemental S can be used as a S source, but it needs time to breakdown in the soil and can also lower soil pH over time. In contrast, ammonium sulfate, potassium sulfate, and gypsum (calcium sulfate) can provide available sulfate to plants directly after application (Laboski 2012). Potassium sulfate is the most expensive of the three fertilizers mentioned above, costing about $755 per ton and contains about 50% P and 18% S (Laboski 2012; Laboski et al. 2020). Ammonium sulfate costs about $294 per ton and contains about 21% N and 24% S (Laboski 2012; Laboski et al. 2020). Calcium sulfate, or gypsum, is the cheapest costing about $233 per ton and percent of Ca can range from about 29% to 22% and S can range from about 24% to 13%, depending on the specific product (Laboski 2012; Laboski et al. 2020). All the immediately available S fertilizers work similarly (Laboski 2012). Beyond price and efficacy, the right choice of which S source to use will be unique for each grower. For example, if a grower needs to side-dress sweet corn with N, ammonium sulfate could be an excellent choice to fulfill both the N and S needs.

When choosing a synthetic fertilizer material to test plant responses to S in our studies, it was important to consider factors such as economics, sustainability, efficacy, and ease of use. Our main priorities were finding a fertilizer that was effective, cheap and versatile. Gypsum, calcium sulfate dihydrate, is an ideal choice for vegetable growers for several reasons: its relatively cheap, can be certified organic, can be dispersed through existing fertilizer equipment, is widely available and it doesn't affect soil pH. In addition to fitting nicely into New York growers' nutrition programs, gypsum can be mined or synthetically produced, which gives the agricultural industry several options for acquiring gypsum. The United States is the second leading producer of mined gypsum worldwide creating about 17 million tons of crude gypsum in 2017 (U.S. Geological Survey 2018). The strong gypsum mining industry in the United States allows growers to have a domestic and affordable option. Gypsum can be purchased in several forms: pulverized gypsum can cost about 134 dollars per ton, for pulverized organic gypsum it can cost about 250 dollars per ton and for pelleted gypsum it can cost about 355 dollars per ton (https://www.usagypsum.com/about-usa-gypsum). In any form, gypsum is a competitive choice for growers due to relatively low costs, ease of use and efficacy.

Soil Texture and Atmospheric Deposition Concentration:

Soil type and texture are an integral part of understanding how nutrients interact with soil particles and ultimately availability to plants. Sulfates interaction with soils and availability to plants is somewhat similar to nitrate. Sulfate is an anion and has a negative charge, making it difficult for negatively charged soil colloids to hold. Therefore, like nitrate, when there is a rain event, or heavy irrigation, sulfate can leach to lower levels of the soil profile and become unavailable to plants (Chao et al. 1962). Coarse textured soils, such as sandy loams, tend to have low clay and organic matter contents, and thus sulfate is typically leached at the greatest rate and to deeper parts of the soil profile (Chao et al. 1962). In contrast, a fine textured soil, high in clay, typically experiences far less leaching and the leachate tends to stay in the top eight inches of the soil even with eight-inch rain events (Chao et al. 1962). Sulfate is also similar to nitrate because of its innate presence in organic matter and mineralization over time. It is estimated that about 1.4-2.3 kg of S can be released each growing season per percent of soil organic matter in soils (Chao et al. 1962; Kaiser & Vetsch 2019). For example, a soil containing two percent organic matter could potentially release about 2.8 to 4.6 kg ha^{-1}, whereas a soil containing four percent organic matter could double the amount of S available (Chao et al. 1962; Kaiser & Vetsch 2019). It is apparent that soils with higher clay content and higher organic matter content have the ability to hold onto sulfate more readily in the soil and provide slow-release sulfate over the growing season. Soils with coarse texture and low organic matter are at risk for increased sulfate leaching as well as low inherent levels of S.

In addition to considering soil texture, it is also important to mention geography. The EPA’s clean air act policies have been successful in reducing the amount of S being released into the atmosphere in all parts of the US. It is important to note that different parts of the country received varying amounts of deposition in a historical sense. For example, in the US from 2000-2002, the Pacific, Rocky Mountain and South-Central regions were receiving about 1.3, 1.2 and 5.7 kg ha^{-1} of S annually, respectively (EPA 2019). During the same time period from 2000-2002, the Northeast, Mid-Atlantic and Midwest were receiving about 10.9, 16.8 and 14.0 kg ha^{-1} of S annually, respectively (EPA 2019). A region's history of atmospheric S deposition could play a vital role in when and where S deficiencies occur. Therefore, it is important to consider soil texture as well as historical atmospheric deposition, among other factors previously mentioned, when considering a soils risk for S deficiencies.

Crop Overview:

New York has a rich history of agriculture with about 7 million acres (2.8 million ha) of farmland, with about 33,500 farms in operation (New York State Department of Agriculture and Markets 2018). New York is a major producer of vegetable crops, ranking 10th among all other states in harvested acres in 2020, which includes both fresh market and processing crops (USDA NASS 2021). The value of utilized vegetable production for 2020 was about $222 million, ranking 7th in the nation (USDA NASS 2021). Although most of upstate New York is significantly active in the agriculture sector, the most economically important vegetable producing areas in New York can be split into three regions: Western region, Finger Lakes/Central region, and Capital/Hudson region (Office of the State Comptroller 2012). For this study, all fertilizer experiments were conducted at Cornell AgriTech, located in Geneva, New York. Geneva is located on the eastern edge of Ontario County and is in the Finger Lakes region.

Ontario county typically experiences about 180 to 200 frost free days annually (Martinson 2005). Generally, the frost-free period is between late April and October, providing a longer growing season than some other areas in upstate New York.

Processing vegetables have historically been of economic importance in this area. In this research project we chose to work with processing English peas, snap beans, and sweet corn, because of their economically importance in the state's processing industry. Processing crops are grown widely in western New York and contribute to a large portion of vegetable acreage in the state, but profit margins are small for processors and growers. Therefore, growers and processors must deal in large quantities and any negative impacts on yields are significant. Sulfur deficiencies impact on protein and chlorophyll production can result in yield decreases and thus could be a serious risk to the processing industry. In addition, fresh market tomatoes were chosen as they are essentially ubiquitous on small, diversified farms and viewed as a more complex, high-quality crop. Further, because of its role in protein synthesis, and photosynthesis, S deficiency could result in lower soluble solids, which could impact quality and taste.

New York consistently ranks in the top three snap bean producing states and in 2017 was listed as the number two producing state with over an 11% share of the entire US snap bean market (Office of Budget and Policy Analysis 2019). In 2017, there was over 10,520 ha of snap beans harvested which was valued at about $34 million (Office of Budget and Policy Analysis 2019). Fresh market snap beans were valued at about $17 million, and processing snap beans were valued at about $16.8 million (Office of Budget and Policy Analysis 2019). Although the total gross value of both fresh market and processing crops are similar, the price at which the grower can sell them varies greatly. In 2017, the price of 100 pounds (CWT) of fresh market snap beans was about $85, whereas 2,000 pounds or one ton of processing snap beans were valued at about $177 or about $9 per CWT (Office of Budget and Policy Analysis 2019). Fresh market produce always sells for a higher price than processing produce for several reasons and the result is processing acres are running on tighter margins. Farmers growing processing crops generally utilize a very efficient and mechanized system with minimal hand labor and sign pre-season contracts with processing companies. In addition, processors are focused on high yields and uniformity.

Processing snap beans are generally grown in rows spaced about 0.75 m apart and seed placed about every 4 cm with the desired goal of 20-27 plants per meter (Ballerstein & Reiners 2018). Typically, snap beans are planted with a vacuum style planter with specialized plates for bean seeds. Currently in New York growers expect to harvest about 7,845 kg ha^{-1} and anything above that threshold is an above average yield (Ballerstein & Reiners 2018). Snap beans are generally classified in three major categories based on color, days to maturity and sieve size. Most snap beans are either a shade of green or yellow, with the yellow beans generally referred to as wax beans by the industry. Snap beans, like other crops, mature at different rates with the industry typically categorizing cultivars into early season, mid-season, and late season crops. The other main metric for snap beans is sieve size, an estimate of the width or thickness of the bean, which is generally split into large, 4-5 sieve; medium, 3-4 sieve; whole, 2-3 sieve; and extra fine, 1-2 sieve.

Different markets prefer different sieve sized beans. For example, it has long been a trend for high-end restaurants and markets to present smaller sieve sized beans as “higher quality”. For our experiments we chose to focus on an industry standard, Huntington a green mid-season bean that falls into the large sieve category. Known for its high yields, disease resistance, straight pods, upright structure and productive response to high fertilizer inputs, Huntington has become a staple for the New York processing industry (http://www.syngenta-us.com/seeds/vegetables/processor-bean).

English peas are another important fresh market and processing crop in New York. In 2017, New York ranked fifth in green pea production and harvested about 3,561 ha (USDA NASS 2017). Similar to snap beans, processing pea production dominated the market in New York with a total of about 3,419 ha of processing peas in 2017 (USDA NASS 2017). In 2018 New York growers produced about $3.35 million worth of both fresh market and processing peas combined. Processing peas production was valued at about $2.86 million and fresh market at about $0.5 million. Processing peas were sold at about $12 per CWT whereas fresh market peas were sold at about $89 per CWT (USDA NASS 2019).

Large scale processing peas would generally be planted with a drill-style planter and for smaller scale operations, like our program, a cone style planter can be utilized. Processing pea seed is planted at a rate of about 1.36 to 1.48 million seed ha^{-1} but can change per cultivar (Ballerstein & Reiners 2018). Processing peas are generally categorized into three major categories with regards to leaf type, days to maturity and sieve size. Pea leaf types generally fall into four main categories: wild type, tendril-less, afila, and afila-tendril-less (Mikic et al. 2011). The market in New York generally pools these four categories into two main categories: afila or normal type (Ballerstein & Reiners 2018). The wild type of pea has both leaves and tendrils. The afila type pea only has tendrils and the normal type (tendril-less) pea only has leaves. One large advantage the afila type pea has is that the tendrils allow the peas to help support each other and create a strong, dense stand of peas. In New York, peas normally remain closer to the ground as temperatures warm which can lead to pathogen and harvesting issues. The afila type's ability to hold upright longer are a main reason they have gained popularity. Peas are generally planted in the spring in New York and the growing season is short, but varieties are still split into early season, mid-season and late season categories. Sieve size categories are not as elaborate as snap beans but range from a sieve size one to seven. For our experiment, we chose to use Portage because it is an industry standard and widely grown for New York processors. Portage, a mid-season variety, consistently produces strong yields and shows resistance to fusarium wilt race 1 (Ballerstein & Reiners 2018, www.critesseed.com).

Similar to snap beans and English peas, sweet corn is a major crop in New York both for fresh market and processing. Sweet corn is one of the few vegetable crops that has been studied for S needs (Brust 2018; Kaiser & Vetsch 2019; Heiniger et al. 2018). In 2017, New York ranked sixth nationwide in overall sweet corn production, with over 10,520 ha harvested valued at about $36.25 million with only about $6.86 million from processing acreage (USDA NASS 2017). In 2018, fresh market sweet corn was sold at about $28 per CWT and processing sweet corn was sold at about $4 per CWT (USDA NASS 2019).

Processing sweet corn is generally planted in rows spaced 0.75 m apart, with in row spacing at about 28 cm between seeds (Ballerstein & Reiners 2018). Corn is generally planted with a vacuum style planter. Overland, a super sweet type, is another New York industry standard. Overland has a strong disease package and consistently produces high yields with acceptable quality for processing (http://www.syngenta-us.com/seeds/vegetables/processor-sweet-corn).

The sole fresh market vegetable examined was tomato. Tomatoes are grown widely throughout New York, with about 1,500 farms growing about 792 ha of field tomatoes (USDA NASS 2017). In addition, tomatoes have a complex flavor and varying quality with heightened consumer interest in cultivar types and flavor, much more so than with any other vegetable tested in our trials. Supermarket tomatoes have long been criticized for a lack of flavor and researchers have recently joined the conversation pointing to genetics (Gao et al. 2019). It is speculated that breeding focused on yield, diseases resistance and shipping has not prioritized flavor (Gao et al. 2019).

In addition to genetics, growing conditions and nutrients can also play a role in yield, quality and flavor. Sulfur's role in amino acid and protein synthesis, photosynthesis, and N uptake and usage, could have direct impacts on yield, soluble solids, titratable acids, as well as other quality and flavor factors (Heckman 2021; Liao et al. 2019; White et al. 2021). Sulfur is also well known to have flavor impacts on specific families of crops. For example, mustard greens or alliums grown in low S conditions will lack their signature spiciness caused by volatile sulfur compounds (McGorrin 2011). In addition, tomatoes grown in New Jersey with a foliar spray of ocean water were deemed more flavorful (J. Heckman, personal communication, 2017). Sulfur's role in plant nutrition, combined with decreased atmospheric deposition and tomatoes heavy feeding habits, made the crop an ideal candidate for testing our hypothesis.

California dominates the US tomato industry growing about 102,385 ha of tomatoes. Florida ranks second at about 11,735 ha and the next closest state produces about 3,186 ha of tomatoes (USDA NASS 2017). Florida, a major tomato producer, is known for sandy soils and thus is likely at a higher risk for S deficiencies than other states with heavier soils (Harris et al. 2010). Therefore, if S deficiencies are impacting tomato quality, Florida growers who remedy such deficiencies, could have a major impact on the tomato market across the nation.

Unlike the other crops in this study, field grown tomatoes are generally started in seed trays in greenhouses and other structures in the spring and transplanted into plastic mulched rows. Rows are typically 1.8 m on center, with plants placed about 0.45 to 0.75 m between plants and can include drip irrigation. Fertilizer can be applied while preparing beds and through fertigation throughout the season. Growers generally aim for about 7,160 to 11,860 per ha and a yield of about 14,000 kg ha^{-1} (Harper & Orzolek 2006). When extension specialists and growers across New York were asked to identify popular tomato cultivars being grown appropriate for the study, Red Deuce, a large, beefsteak style tomato was chosen. Red Deuce is an early/mid-season variety, that produces large, globed shape fruit and exhibits a strong disease package (www.harrisseeds.com).

The limited research in the literature of both S needs for vegetable crops and S needs in New York prompted our studies. We focused on economically important processing vegetables because of their importance to New York's economy as well as the importance of fertility management in low value processing crops. We also tested tomatoes because of the potential impact S deficiency could have on taste. The objectives of this study were to identify if S deficiencies were already impacting English pea, snap bean, sweet corn and tomato production, if supplemental S would improve yield and other quality factors, and if gypsum would be an effective S source.

WORKS CITED

Astill, G., Minor, T., & Thornsbury, S. (2019). Changes in U.S. produce grower food safety practices from 199 to 2016. Food Control, 104, 326-332. https://doi.org/10.1016/j.foodcont.2019.05.007

New York State Department of Agriculture and Markets. (2018). 2018 Annual Report. https://www.agriculture.ny.gov/system/files/documents/2019/10/2018-annual-report.pdf

Ballerstein, J.W., & Reiners, S. (2018). New York State 2018 Processing Pea Cultivar Trial Report. https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/1/7446/files/2019/07/NYpearep18.pdf

Ballerstein, J.W., & Reiners, S. (2018). New York State 2018 Processing Snap Bean Cultivar Trial Report. https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/1/7446/files/2019/07/NYbeanrep18.pdf

Ballerstein, J.W., & Reiners, S. (2018). N.Y.S. 2018 Processing Sweet Corn Variety Replicated and Observation Trial Summary. https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/1/7446/files/2019/07/NYcornrep18.pdf

Beegle, D. (2017). Estimating Manure Application Rates. https://extension.psu.edu/estimating-manure-application-rates

Brust, J. (2018). Sulfur Deficiency in Sweet Corn. University of Delaware: Weekly Crop Update. https://sites.udel.edu/weeklycropupdate/?p=12411

Camberato, J., & Casteel, S. (2017). Soil Fertility Update: Sulfur Deficiency. https://www.agry.purdue.edu/ext/corn/news/timeless/sulfurdeficiency.pdf

Chao, T.T., Harward, M.E., & Fang, S.C. (1962). Movement of S35 Tagged Sulfate Through Soil Columns. Soil Science of America Journal, 26(1), 27-32. https://doi.org/10.2136/sssaj1962.03615995002600010008x

Environmental Protection Agency (EPA). (2018). Our Nations Air 2017. https://gispub.epa.gov/air/trendsreport/2018/#welcome

Environmental Protection Agency (EPA). (2019). Progress Report: Acid Deposition. https://www3.epa.gov/airmarkets/progress/reports/acid_deposition_figures.html#figure3

Environmental Protection Agency (EPA). (1990). A Retrospective, 1970-1990. https://archive.epa.gov/epa/aboutepa/epa-retrospective-1970-1990.html

Food and Drug Administration (FDA). (2018). FSMA Final Rule for Preventative Controls for Human Food. https://www.fda.gov/food/food-safety-modernization-act-fsma/fsma-final-rule-preventive-controls-human-food

Gao, L., Gonda, I., Sun, H., et al. (2019). The tomato pan-genome uncovers new genes and a rare allele regulating fruit flavor. Nat Genet, 51(6), 1044-1051. https://doi.org/10.1038/s41588-019-0410-2

Goldy, R. (2013). Knowing nutrient mobility is helpful in diagnosing plant nutrient deficiencies. https://www.canr.msu.edu/news/knowing_nutrient_mobility_is_helpful_in_diagnosing_plant_nutrient_deficienc

Harper, J.K., & Orzolek, M. (2006). Tomato Production. https://extension.psu.edu/tomato-production

Hawkesford, M.J. (2003). Transporter gene families in plants: the sulphate transporter gene family – redundancy or specialization? Physiologia Plantarum, 117(2), 155-163. https://doi.org/10.1034/j.1399-3054.2003.00034.x

Hakesford, M.J., & De Kok, L.J. (2006). Managing Sulphur metabolism in plants. Plant, Cell and Environment, 29 (3), 382-395. https://doi.org/10.1111/j.1365-3040.2005.01470.x

Harris, W.G., Chrysostome, M., Obreza, T.A., & Nair, V.d.. (2010). Soil Properties Pertinent to Horticulture in Florida. Horticulture Technology, 20(1), 10-18. https://doi.org/10.21273HORTTECH.20.1.10.

Heckman, J. (2021). Sulfur Nutrition and Soil Fertility Management for New Jersey Crops. https://njaes.rutgers.edu/e365/

Heiniger, R.W., Crozier, C., Hardy, D., Walls, B., & Reich, R. (2018). Sulfur Deficiency Symptoms Emerging in Corn. https://corn.ces.ncsu.edu/sulfur-deficiency-symptoms-in-emerging-corn/

Hergert, G. (2015). WWII Nitrogen Production Issues In Age of Modern Fertilizers. https://cropwatch.unl.edu/fertilizer-history-p3

Johnson, G. (2018). Sulfur and Vegetable Crops. https://sites.udel.edu/weeklycropupdate/?p=12050

Johnson, R. (2019). Foodborne Illnesses and Outbreaks from Fresh Produce. https://fas.org/sgp/crs/misc/IF11092.pdf

Kaiser, D.E., & Vetsch, J.A. (2019). Sulfur for Minnesota Soils. https://extension.umn.edu/micro-and-secondary-macronutrients/sulfur-minnesota-soils

Kelly, W.C. (1990). Minimal Use of Synthetic Fertilizer in Vegetable Production. HortSceince, 25(2), 168-169. Retrieved from file:///Users/mwr54/Downloads/[HortScience]%20Minimal%20Use%20of%20Synthetic%20Fertilizers%20in%20Vegetable%20Production.pdf

Ketterings, Q.M., Godwin, G., Gami, S., Dietzel, K., Lawrence, J., Barney, P., Klicer, T., Stanyard, M., Albers, C., Cherney, J.H., Cherney, D., & Czymmek, K.J. (2012). Soil and Tissue Testing for Sulfur Management of Alfalfa in New York State. Soil Science Society of American Journal, 76(1), 298-306. https://doi.org/10.2136/sssaj2010.0437

Laboski, C.A.M., (2012). 2012 Sulfur Fertilizer Price Comparison for Alfalfa. https://ipcm.wisc.edu/blog/2012/04/2012-sulfur-fertilizer-price-comparison-for-alfalfa/

Laboski, C.A.M., & Peters, J.B. (2012). Nutrient Application Guideline for Field, Vegetable, and Fruit Crops in Wisconsin. https://walworth.extension.wisc.edu/files/2018/11/Nutrient-Application-Guidelines-for-Field-Vegetable-Fruit-Crops-in-WI-A2809.pdf

Liao, L., Dong, T., Qiu, X., Rong, Y., Wang, Z., & Zhu, J. (2019). Nitrogen Nutrition is a key modulator of sugar and organic acid content in citrus fruit. PLOS ONE 14(10), e0223356. https://doi.org/10.1371/journal.pone.0223356

Likens, G.E. & Bailey, S. (2013). The Discovery of Acid Rain at the Hubbard Brook Experimental Forest: A story of Collaboration and Long-term Research. USDA Forest Service Experimental Forests and Ranges: Research for the Long Term. In: Hayes, D., Stout, S., Crawford, R., Hoover, A. (eds) USDA Forest Service Experimental Forests and Ranges. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-1818-4_20

Likens, G.E., Bormann, F.H., & Johnson, N.M. (1972). Acid Rain. Environment: Science and Policy for Sustainable Development, 14(2), 33-40. https://doi.org/10.1080/00139157.1972.993301

Marschner, P. (2012). Marschner's Mineral Nutrition of Higher Plants. Academic Press. https://doi.org/10.1016/C2009-0-63043-9

Martinson, T.E. (2005). Macroclimate in New York State and Site Suitability. https://grapesandwine.cals.cornell.edu/sites/grapesandwine.cals.cornell.edu/files/shared/documents/macroclimate-and-site-suitability-in-NY.pdf

McCauley, A., Jones, C., & Jacobsen, J. (2009). Plant Nutrient Functions and Deficiency and Toxicity Symptoms. https://mtvernon.wsu.edu/path_team/Plant-Nutrient-Functions-and-Deficiency-and-Toxicity-Symptoms-MSU-2013.pdf

McGorrin, R.J. (2011). The Significance of Volatile Sulfur Compounds in Food Flavors. American Chemical Society. https://doi.org/10.1021/bk-2011-1068.ch001

Mezey, E.J., Singh, S., & Hissong, D.W. (1976). Fuel Contaminates Volume 1 – Chemistry. https://nepis.epa.gov/Exe/ZyNET.exe/91015WRL.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1976+Thru+1980&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C76thru80%5CTxt%5C00000024%5C91015WRL.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL

Mikic, A., Mihailovic, V., Cupina, B., Kosev, V., Warkentin, T., McPhee, K., Ambrose, M., Hofer, J., & Ellis, N. (2011). Genetic Background and Agronomic Value of Leaf Types in Pea (Pisum sativum). Ratarstvo i Povrtarsto, 48, 275-284. https://doi.org/10.5937/RATPOV1102275M

New York Farm Bureau. (2019). New York Agriculture. https://www.nyfb.org/about/about-ny-ag

Office of Budget and Policy Analysis. (2019). A Profile of Agriculture in New York State. https://www.osc.state.ny.us/reports/economic/agriculture-report-2019.pdf

Office of the New York State Comptroller. (2012). Agriculture By the Numbers: New York Farming is Big Business. http://www.lifb.com/Portals/1/Dinapoli.pdf

Ritchie, H., Roser, M., & Rosado, P. (2020). Energy Production & Changing Energy Sources. Our World in Data. Retrieved from https://ourworldindata.org/energy-production-and-changing-energy-sources

Rosen, C.J., & Bierman, P.M. (2005). Nutrient management for fruit and vegetable crop production: Using manure and compost as nutrient sources for vegetable crops. https://conservancy.umn.edu/handle/11299/200639

Rouhier, N., Lemaire, S.D., & Jacquot, J.P. (2008). The Role of Glutathione in Photosynthetic Organisms: Emerging Functions of Glutaredoxins and Glutathionylation. Annual Review of Plant Biology, 59(1), 143-166. https://doi.org/10.1146/annurev.arplant.59.032607.092811

Schonhof, I., Blankenburg, D., Muller, S., & Krumbein, A. (2007). Sulfur and nitrogen supply influence growth, product appearance, and glucosinolate concentration of broccoli. J. Plant Nutr. Soil Sci. 170(1), 155-163. https://doi.org/10.1002/jpln.200620639

Schulte, E.E., & Kelling, K.A. (1992). Soil and Applied Sulfur. http://corn.agronomy.wisc.edu/Management/pdfs/a2525.pdf

Taran, N., Okanenko, A., Musienko, N. (2000). Sulpholipid reflects plant resistance to stress-factor action. Biochemical Society Transactions. 28(6), 922-924. https://doi.org/10.1042/bst0280922

Thangasamy, A., Sankar, V., Lawande, K.E.. (2013). Effects of sulphur nutrition on pungency and storage life od short day onion (Allium cepa). Indian Journal of Agricultural Sciences, 83, 1086-1089. Retrieved June 13, 2022, from https://www.researchgate.net/publication/286969836_Effect_of_sulphur_nutrition_on_pungency_and_storage_life_of_short_day_onion_Allium_cepa

United States Department of Agriculture-National Agricultural Statistics Service (USDA NASS). (2017). 2017 Census of Agriculture-State Data. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_2_US_State_Level/st99_2_0029_0029.pdf

United States Department of Agriculture-National Agricultural Statistics Service (USDA NASS). (2019). 2018 State Agriculture Overview. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEW%20YORK

United States Department of Agriculture-National Agricultural Statistics Service (USDA NASS). (2021). Vegetables 2020 Summary. https://downloads.usda.library.cornell.edu/usda-esmis/files/02870v86p/0r967m63g/sn00bf58x/vegean20.pdf

U.S. Geological Survey. (2018). Mineral Commodity Summaries: Gypsum. https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/gypsum/mcs-2018-gypsu.pdf

Vossen, P. (n.d). What is a Chemical Fertilizer? http://cesonoma.ucanr.edu/files/27201.pdf

Duncan, A. (2008). Superphosphate – Making superphosphate. https://teara.govt.nz/en/diagram/15566/superphosphate-manufacture

Wardlaw, I.F., & Passioura, J.B. (1976). Transport and Transfer Processes in Plants. Academic Press Inc. https://doi.org/10.1016/B978-0-12-734850-6.X5001-1

White, C., Spargo, J., Wells, H., Sanders, Z.P., Rice, T., & Beegle, D. (2021). Agronomy Facts 80: Sulfur Fertility Management for Grain and Forage Crops. https://extension.psu.edu/sulfur-fertility-management-for-grain-and-forage-crops

CHAPTER 2

Gypsum as a Sulfur Supplement for Three Important New York Processing Crops

Abstract:

Sulfur (S) deposition has declined over the past decades and research is needed to evaluate S responsiveness of processing vegetables important to New York's vegetable production. Our objective was to evaluate whether supplemental S resulted in yield and quality increase of economically important processing crops in New York, including English peas (*Pisum sativum*), snap beans (*Phaseolus vulgaris*), and sweet corn (*Zea mays*). Gypsum, a calcium sulfate compound, was chosen as the S source because it is cheap, easily added to fertility plans, can be certified organic, and does not change the soil pH like most other S amendments. Gypsum was spread by hand no earlier than seven days prior to planting at a rate that supplied 68 kg ha^{-1} of actual sulfate. Crops were harvested close to peak maturation time. All crops were weighed and evaluated for maturity and other quality metrics. The metrics of yield and other quality indicators, unique to each crop, were compared. No statistically significant differences between treatments were observed in yield, quality, or maturity metrics in any of the three crops. The results suggest that currently in New York, vegetable growers with fine textured soils, similar to those at Cornell AgriTech, are unlikely to experience yield or quality benefits from adding gypsum to their fields.

Introduction:

Sulfur is categorized as a plant macronutrient, along with nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). Sulfur plays a diverse role in plants, ranging from protein synthesis and chlorophyll production to secondary metabolites that help plants deal with stress. Sulfur is notably involved in the synthesis of amino acids cysteine and methionine. Sulfur has also gained research attention for secondary metabolites, such as glutathione, which is a powerful antioxidant beneficial to both plants and humans (Marschner 2012).

From 2015 to 2017, the northeastern part of the US received about 3 kg ha^{-1} of S from atmospheric deposition (EPA 2019). Comparatively, in the years 2000 to 2002, deposition averaged about 12 kg ha^{-1} of S (EPA 2019). This drastic reduction has potentially increased the risk of crop S deficiency. Sulfur deficiencies have been recorded in field in sweet corn (*Zea mays*), alfalfa (*Medicago sativa)*, and watermelon (*Citrullus lanatus)*, among other crops around the country (Ketterings et al. 2012; Brust 2018; Brust 2019; Heckman 2021). Fields with coarse textured soils typically contain less organic matter and are more likely to exhibit S deficiencies (Camberato & Casteel 2017; Miller & Shober 2019). Research with 2nd cutting alfalfa in New York showed that supplemental S is necessary when soil S levels was less than 8 ppm (Ketterings et al. 2012). Ketterings and colleagues concluded that out of the six S tests, the 0.01 mol L^{-1} $CaCl_2$ extraction method was most accurate in identifying S deficient alfalfa fields (Ketterings et al. 2012). The threshold of 8 ppm soil S level for alfalfa is the only current soil-based recommendation for S. Establishing a critical value of soil S for other crops is useful, especially given S deficiencies are becoming more common nationally (Brust 2018; Camberato & Casteel 2017; Heckman 2021).

In 2017, New York ranked 12th in vegetable production across the US. Snap beans and sweet corn account for the largest vegetable production in New York at 9,672 ha and 10,267 ha, respectively (USDA NASS 2017). Both snap bean and sweet corn production in New York typically rank among the top five states producing such crops and in 2017 snap bean production was second in the nation (USDA NASS 2017). Snap bean production generated about $34 million dollars and sweet corn production generated about $36 million (USDA NASS 2018). Not far behind, English pea production was at about 3,593 ha, the fifth largest planted acreage of any vegetable crop in New York and sixth in the United States. English peas generated about $3 million in 2017 (USDA NASS 2017). Together these three crops account for about 20% of the farmgate value of New York grown vegetables (USDA NASS 2017). We focused on processing cultivars as this industry runs on small margins, making soil fertility critical. If S deficiency becomes common, it could be detrimental to yield and quality. Although we chose processing cultivars, crops response to S is relevant to both processing and fresh market cultivars.

Historically fertilizer regimes have predominately focused on three macronutrients, including N, P and K. Each year it is not uncommon for a vegetable grower to apply a crop specific blend of NPK without any additional nutrients as the base strategy. Although some growers will take annual soil samples for nutrient testing, the actual practice of soil testing is quite variable. Applying fertilizer without measuring soil nutrients, leaves the grower vulnerable to other macro-and micro-nutrient deficiencies. In addition, the basic soil sample package offered by many laboratories does not include S and those that do include S, offer a different test than the $CaCl_2$ test. Taking all three of these factors into consideration, along with the decreased atmospheric deposition of S, there is potential for S deficiencies, which needs to be evaluated.

Our objectives were to test if economically important New York processing crops show a quality or yield response to supplemental S, provided as gypsum. English peas, snap beans and sweet corn were chosen as test crops because of their economic importance in New York as well as their large share of processing acres in the state.

Materials and Methods:

Experiments were conducted at Cornell AgriTech in Geneva NY. The soils mostly consist of Lima silt loam and Honeoye loam, both finer textured soils with medium to high clay levels. Honeoye loam is taxonomically classified as "fine-loamy, semiactive, mesic Glossic Hapludalfs" (USDA 2020) found on about 222,577 hectares in New York and is used for crops such as, corn, soybean, wheat, vegetables, fruits, and different types of animal forage (USDA 2020). Honeoye loam is deep and well drained, with limestone and calcareous shale as the predominate bedrock (USDA 2020). Lima silt loam is taxonomically, "Fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalfs" (USDA 2011), and described as being a deep and moderately well drained soil, with limestone and calcareous shale as the predominate bedrock (USDA 2011). Lima silt loam is farmed across the state for field crops, vegetables, fruits, and animal forages (USDA 2011).

Soil samples were taken from all fields used during both the 2018 and 2019 growing seasons. In 2018 and 2019, pre-season soil samples were taken as close to planting date as possible. In 2019, soil samples were taken again in the fall. Standard metrics, including pH and organic matter were measured, and the Morgan soil test was utilized to measure extractable P, K, Ca, and Mg. In addition, a 0.01 mol L^{-1} $CaCl_2$ extraction method, or the 'Cornell Sulfur Test', was used to quantify available S in soils (Ketterings et al. 2012). Ketterings and colleagues discovered that alfalfa could benefit from S fertilization if soil test S was less than 8 parts per million (ppm) in certain scenarios and found that 8 parts per million (ppm) using the 0.01 mol L^{-1} $CaCl_2$ extraction method (Ketterings et al. 2012). A 'Turf-Tech International' soil sampling device was used to extract soil cores from 0 to 20 cm. At least 15 soil cores were taken and then mixed for each field tested. Samples were analyzed for available S using the 0.01 mol L^{-1} $CaCl_2$ extraction method at the Nutrient Management Spear Program Laboratory at Cornell University.

The English pea fields were fall plowed, then chisel plowed and disked twice the following spring. Prior to the second disk tillage, 8-14-21 fertilizer was broadcasted at a rate of 448 kg ha^{-1} and worked into the soil. Portage peas were used in both years, planted on April 28th in 2018 and May 8th in 2019. The peas were planted with a seven row Modified Hedge 80 cone style planter in both years. The plots were seven rows wide, with a width of 106.7 centimeters and length of 4.6 meters with a 91.4 cm buffer zone. After planting, herbicide was applied to the fields for weed control. A mixture of Raptor, Thistrol, Assure and Basagran was applied following grower/extension recommendations (Reiners et al. 2019).

The trial was configured using a complete randomized split block design. The trial had two treatments: a S treatment and a control. In the S treatment, gypsum was applied at a rate that supplied 68 kg ha^{-1} of actual S in addition to a standard fertilizer regime. The control treatment was a standard grower fertilizer regime with no gypsum added. Each treatment was replicated five times in the trial. The same plot design was used for both the 2018 and 2019 growing seasons. During the growing period, chlorophyll levels were estimated using a 'Minolta SPAD 502' meter with 'FieldScout' software. The SPAD readings were taken three times, starting about three weeks before harvest and done on a weekly interval. For each plot, 10 random plants were chosen, and the youngest mature leaf was measured. For yield and quality metrics, 1.5 m sections were measured and harvested. Plant and pods were weighed in the field, then pods were hand picked off plant, then weighed and then shelled. The berries were weighed again and a sample size around 0.3 kg was taken and run through a hand powered sieve. Each individual sieve size was then weighed. A random sample was taken from the larger container and run through the tenderometer machine or 'Model TG4EI Integrating Texturegauge' to measure maturity, which correlates to starch levels and ideal harvest timing.

For the snap bean study, preseason soil samples were taken in 2018 and 2019. In 2019, a postharvest sample was taken August 20th. The fields used for snap beans were first moldboard plowed in the spring, then chisel plowed, and finally disked. At the time of planting, the equivalent of 336 kg ha^{-1} of 15-5-10 was banded 5 cm below and 5 cm to the side of the seeds. The snap beans were planted with a two row 'Monosem Vacuum Planter'. In 2018, 'Huntington' snap beans were planted on May 24th, and in 2019 on June 5th. Rows were spaced 0.76 m apart and plots were 4.57 m long, with the goal of 20-26 plants per meter. After planting, an application of 'Dual' was made for weed control following Cornell guidelines (Reiners et al. 2019). About 30 days after planting the trials were cultivated for extra weed control.

The trial was configured using a complete randomized split block design. The trial had two treatments: a sulfur treatment and a control. The sulfur treatment was gypsum applied at a rate that supplied 68 kg ha^{-1} of actual sulfate, in addition to a standard fertilizer regime. The control treatment was the standard grower fertilizer regime with no sulfur added. Each treatment was replicated 5 times in the trial. The same plot design was used for both the 2018 and 2019 growing seasons. During the growing period, chlorophyll levels were estimated using a 'Minolta SPAD 502' meter with 'FieldScout' software. The SPAD readings were taken three times, starting about three weeks before harvest and done on a weekly interval. For each plot, 10 random plants were chosen, and the youngest mature leaf was measured. For yield and quality metrics, 1.5-meter sections were measured and harvested. Pods were picked from all plants in the subplot and the pods weighed. Pods were then snipped to remove ends and then graded which separates pods by sieve size. Individual sieve sizes were then weighed and a sample of ten beans taken from the four and five sieve bean samples. 'Huntington' is categorized in the large sieve bean category and therefore majority of its pods are harvested at the four and five sieve stage. For both the four and five sieve bean samples, 10 beans are randomly chosen, and one seed is taken from one bean and the ten seeds are lined up and measured for length, which corresponds to ideal maturity for harvest. For large sieve beans, processors' aim for a seed length in the four-sieve bean category at about 90 mm and for the five-sieve beans about 100 mm.

In the sweet corn trial, 'Overland', a super sweet industry standard, was the variety chosen. In 2018 and 2019, preseason soil samples were taken, and a postharvest sample taken in 2019 on August 20th. Both the 2018 and 2019 trials were planted on June 17th. Fields used for corn trials were conventionally tilled with a moldboard plow, shanks, and disks. The trials were planted with a two row 'Monosem Vacuum Planter'. A 15-5-10 fertilizer was banded 5 cm below and 5 cm to the side during planting at a rate of 392 kg ha^{-1}. Plots consisted of two rows, with rows spaced at 76 cm and 12.1 m in length. Desired plant spacing was about 27.9 centimeters. Dual was applied at planting and Bicep Lite was applied to the trial post emergence for weed control at the suggested label rate (Reiners et al. 2019). The field was also cultivated about 30 days after planting, to provide weed control, and incorporate a side-dressed application of ammonium nitrate (33-0-0) fertilizer at a rate of 124 kg ha^{-1}.

The trial was configured as a complete randomized block design with two treatments: a sulfur treatment and a control. The sulfur treatment was gypsum applied at a rate that provided 68 kg ha^{-1} of actual sulfate, in addition to a standard fertilizer regime. The control treatment was a standard grower fertilizer regime with no sulfur added. Each treatment was replicated five times in the trial. The same plot design was used for both the 2018 and 2019 growing seasons. During the growing period, chlorophyll levels were estimated using a 'Minolta SPAD 502' meter with 'FieldScout' software. The SPAD readings were taken three times, starting about three weeks before harvest and done on a weekly interval. For each plot, 10 random plants were chosen, and the youngest mature leaf was measured. For yield and quality metrics, 10 mature ears were harvested from two rows in a 1.55-meter section, with the goal of acquiring mature ears. The 10-ear plot sample was weighed 'green' in the field and then husked and weighed again. Ear length and the base diameter were measured.

A statistical analysis was executed for all crops using RStudio software and in consultation with Cornell Statistical Consulting Unit. Linear models were used to compare the sulfur treatment and control treatment across several categories. For all crops, yield and SPAD readings were compared between treatments. Maturity and quality metrics were compared among treatments in categories unique to each crop. For English peas, we compared total biomass, pod weight, berry weight, and the tenderometer readings. For snap beans, we compared overall yield and percent beans in the 4 and 5 sieve categories, and seed length. For sweet corn, we compared unhusked weight, husked weight, average ear length, and average ear diameter at base. An alpha of 0.05 was used.

Results, Discussion and Graphs:

Addition of S in the English pea trial did not result in statistically significant responses in any category measured. The pea field in 2018, sampled on April 25th, tested at 4.1 ppm S and in 2019, 3.6 ppm on May 10th and 1.4 ppm on August 21st. The S treatment was trending towards improving total biomass but was not statistically significant with a p-value of 0.28 (Figure 1). Although not significant, S addition could be improving overall biomass in some scenarios. In Figure 2, the pod weight comparison showed a p-value of 0.70, which suggests S had no impact on pod yield. When comparing total biomass yield to pod yield, the results suggested S addition did not increase pod yield but may have been increasing overall plant biomass in some instances. For berry yield, a comparison of the treatments showed an insignificant p-value of 0.49, which agrees with the pod yield results which were not affected by the S addition (Figure 3). Similarly, SPAD readings were not different between treatments (Figure 4).

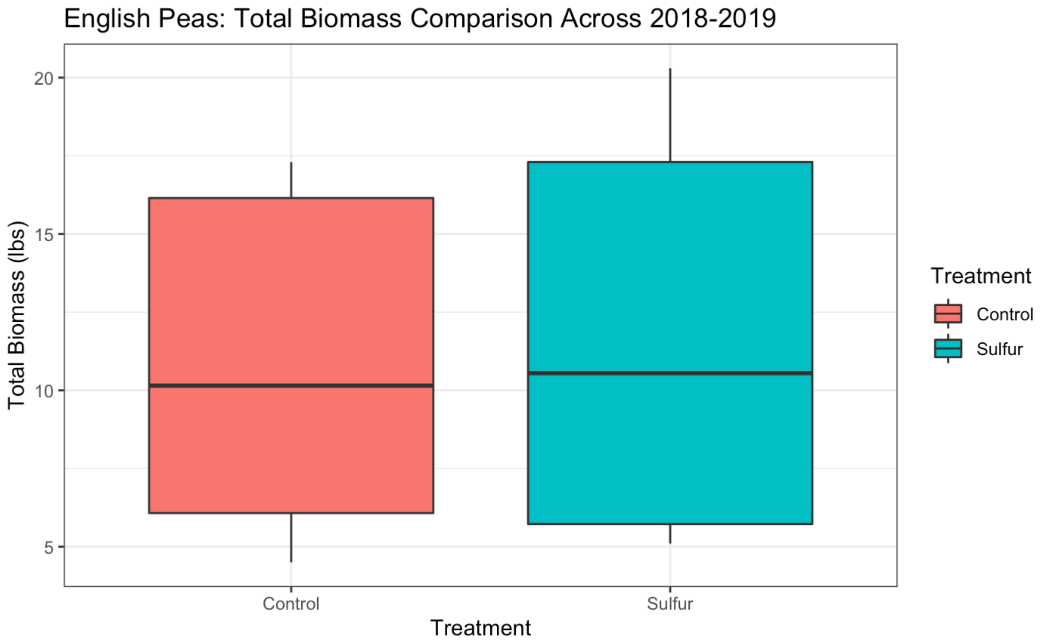

Figure 1: Total biomass is the weight of the total plant pulled at ground level with pods still on the plant from our 5-foot harvest plot sections. The data is combined for 2018 and 2019. Linear regression models used to compare treatment means (p-value = 0.28).

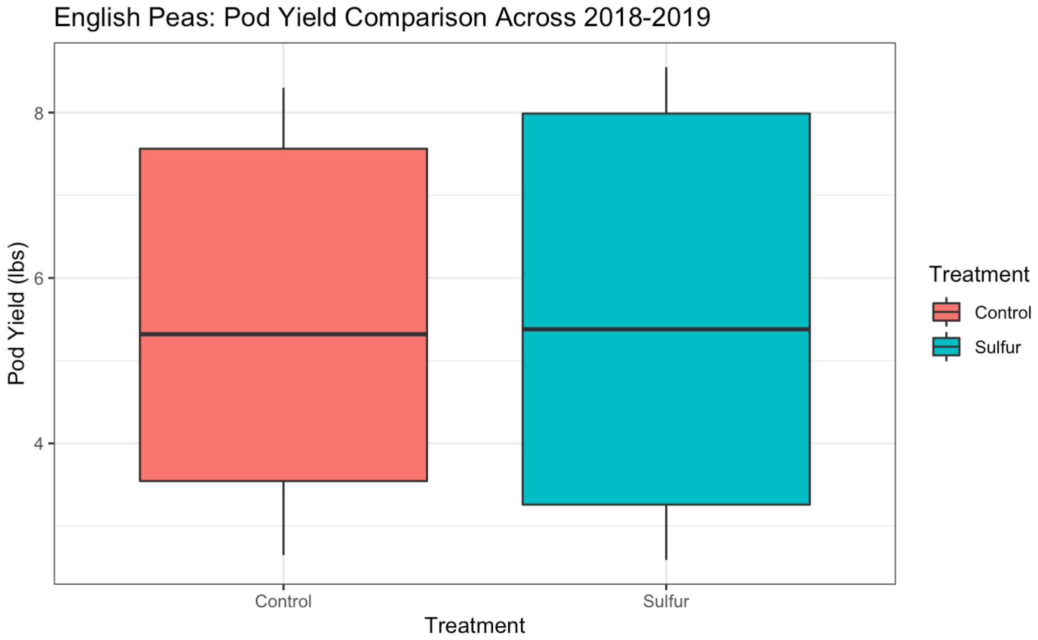

Figure 2: Pod yield is the weight of all pods hand-picked from the plants in our 5-foot harvest plot sections. Data combined for 2018 and 2019. Linear regression model was used to compare treatment means (p-value = 0.70).

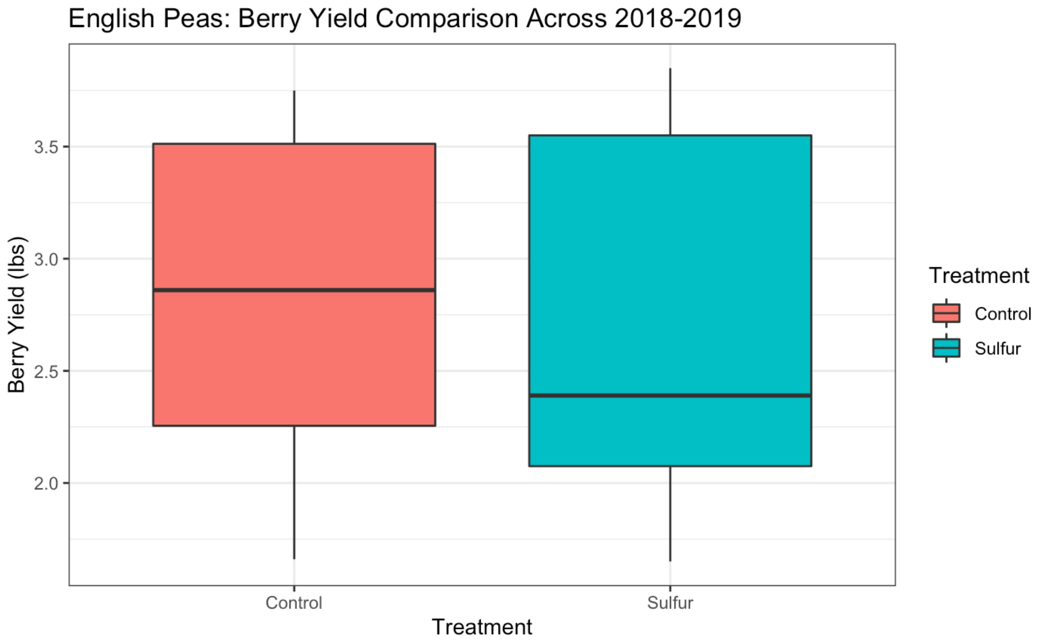

Figure 3: Berry yield is the weight of all the berries from the pods from our 5-foot harvest plot section. Pods are run through sheller machine, berries are collected and weighed. Data combined for 2018 and 2019. Linear regression model used to compare treatment means (p-value = 0.49).

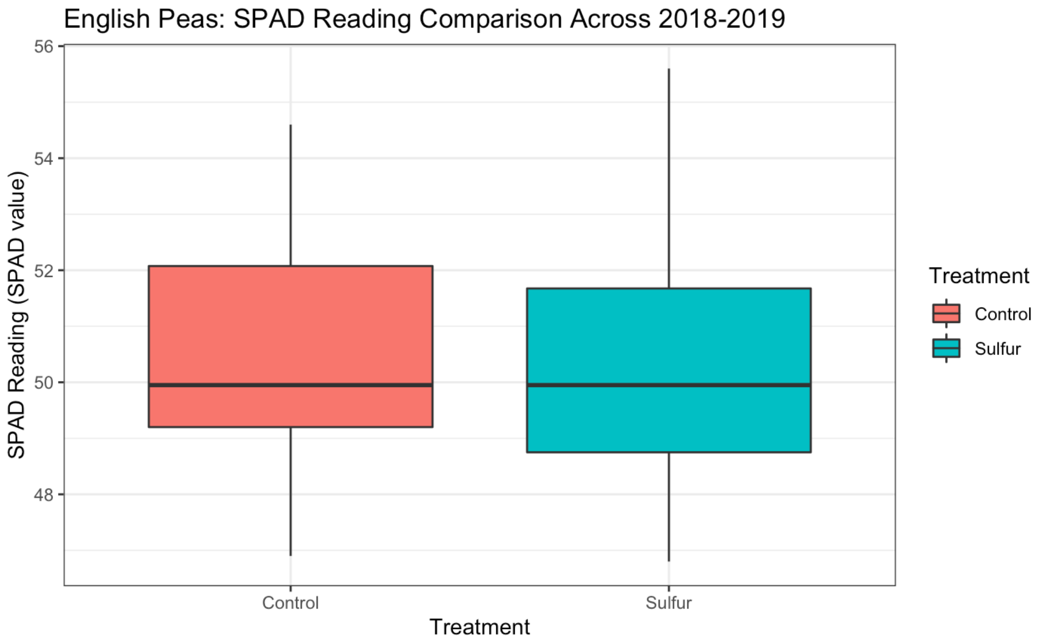

Figure 4: SPAD readings were taken three weeks before harvest and use a greenness measurement to estimate chlorophyll levels. Readings were taken from the youngest, most recently mature leaf. Data combined for 2018 and 2019. Mixed linear regression model used to compare treatment means (p-value = 0.98).

Maturity, or sugar to starch ratio, is measured by a tenderometer or texture gauge. Currently processors recommend harvest at a value of 110. Harvesting at specific tenderometer readings correlates to important factors such as: maximum yield, sugar to starch balance, freezing quality, color, and taste. For example, if English peas are harvested at a tenderometer reading of 140, the yield would be higher than a 110 harvest, but the peas could be more bitter, starchy, hard and there could be more splitting when shelling and freezing. The comparison of treatments with and without S showed no statistically significant difference. However, the S addition showed a trend toward higher tenderometer readings on average with a p-value of 0.23 (Figure 5) which implies an effect on maturity date. More research is necessary to test this hypothesis.

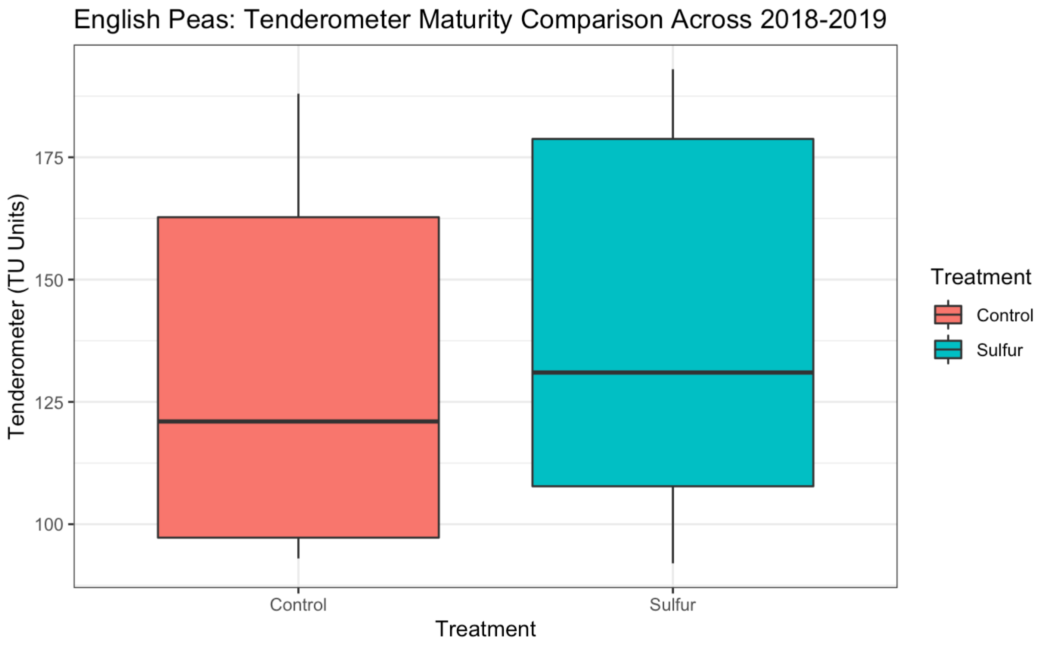

Figure 5: Tenderometer reading is a sugar to starch ratio estimate, which correlates with maturity and ideal harvest time. Random sub-samples of berries were taken from each test plot and run through the Tenderometer machine. Data from 2018 and 2019. Linear regression model used to compare treatment means (p-value = 0.23).

Overall, S supplementation had no statistically significant impact on English peas in any of the metrics that we measured. There were possible trends of S impacting overall biomass and maturity, but additional research is needed to test these hypotheses. Our trial showed that the critical soil test S level is lower than the soil S threshold for alfalfa at second cutting (8 ppm) determined by Ketterings et al. (2012). Additional research is needed on multiple crops to determine critical soil S levels.

In addition to crop specific research, research is also needed on plants respone to S supplementation across soil types. The literature generally describes coarse textured, sandy soils with low organic matter as greater risk for S deficiencies (Chao et al. 1962; Marschner 2012; Laboski and Peters 2012; Camberato and Casteel 2017; and Kaiser and Vetsch 2019). The current understanding in the literature suggests a lower ppm threshold in coarse textured soil with low organic matter versus a higher threshold in finer textured soils with higher organic matter. This is due to S inherently being present in organic matter and is held more readily in soils with higher clay and organic matter content. Our trials were conducted on fine textured soils only, with soil S levels of 4.1 ppm and 3.6 ppm in the spring of 2018 and 2019, respectively.

The snap bean trial conducted in 2018 and 2019, showed no statically significant differences among treatments. A soil sample taken on March 25th, 2018, resulted in a reading of 5.0 ppm soil sulfur level, and a May 10th, 2019, sample provided a reading of 3.6 ppm. A late season sample taken on August 21st, 2019, resulted in a 0.9 ppm reading. For snap beans, we compared four major metrics: total yield, percentage of 4 and 5-seive beans, SPAD readings and seed length. Overall yield is a major factor for both processors and growers’ profitability. In our trial, there was no significant difference, in yield with a p-value of 0.95 (Figure 6). Similarly, percent 4-5 sieve and SPAD readings showed no difference with a p-value of 0.79 and 0.33 respectively (Figure 7 and 8). The last metric measured was seed length. Seed length helps identify pod maturity and ensures plants were harvested at the optimum time. The comparison among treatments and seed length was also insignificant with a p-value of 0.49 (Figure 9).

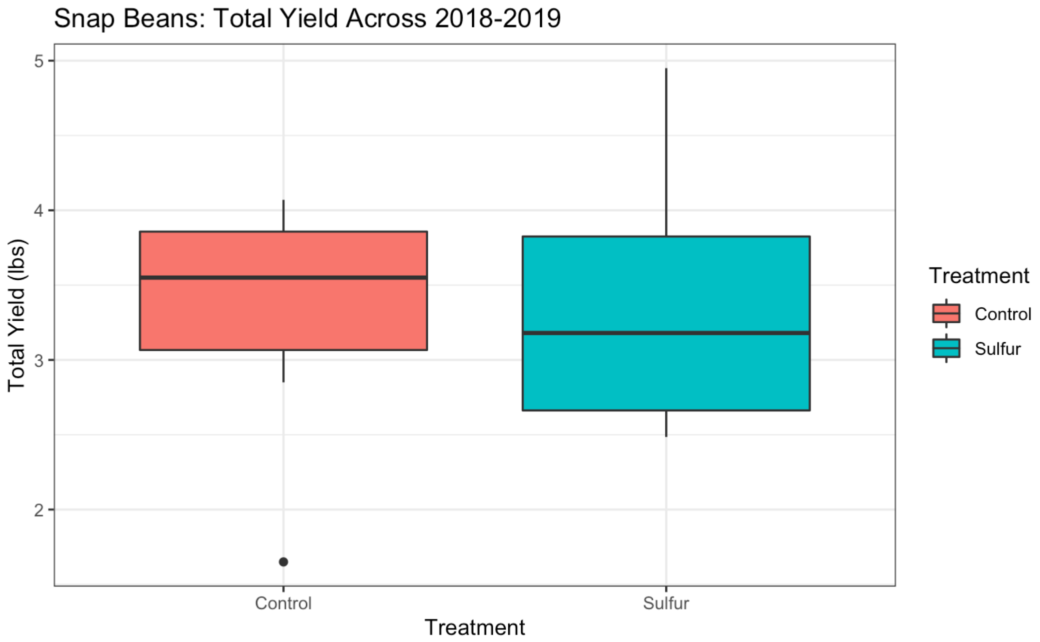

Figure 6: Total yield is the weight of all the snap bean pods harvested from our 5-foot harvest test section, each of the 5 reps for each treatment measured separately. Data combined for 2018 and 2019. Linear regression model used to compare treatment means (p-value = 0.95).

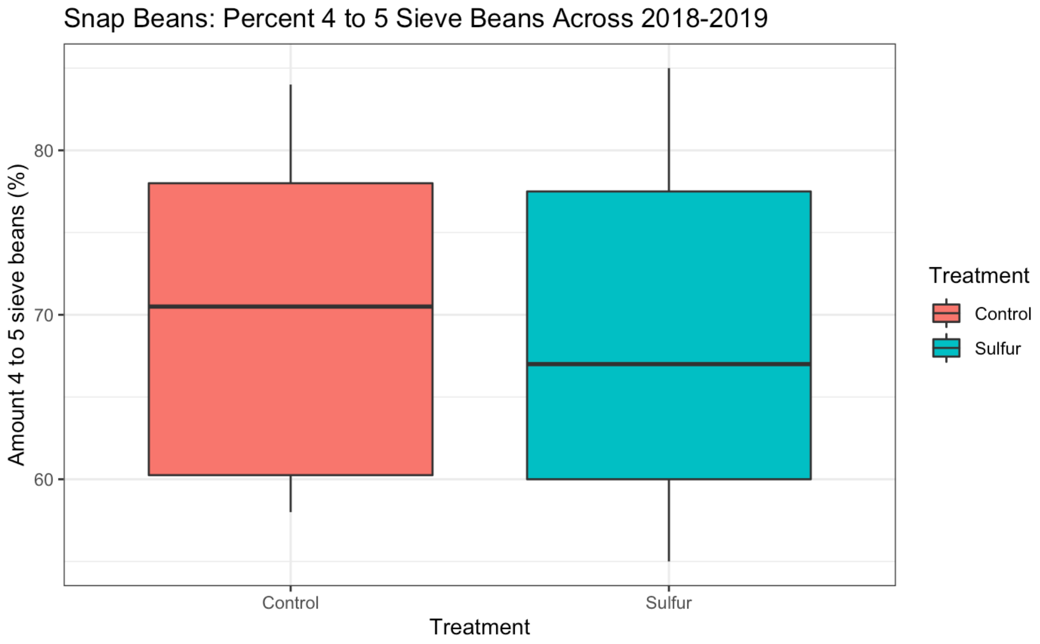

Figure 7: 5-foot sections of snap beans were harvest from 5 control and 5 S treated test plots. Sieve sizes are separated in a grading machine by diameter. 4 to 5 sieve beans are the main size for large sieve beans like the one used for this trial. 4 to 5 sieve bean weights were compared to other sieve size percentages and compared across treatments. Data combined for 2018 and 2019. Linear regression model used to compare treatment means (p-value = 0.79).

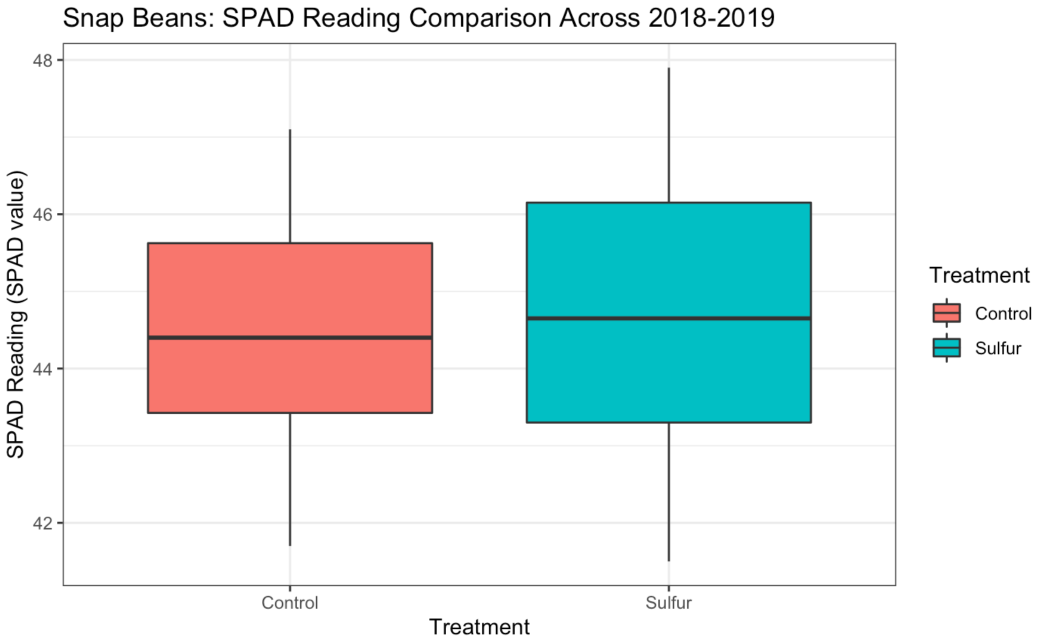

Figure 8: SPAD readings were taken three weeks before harvest and use a greenness measurement to estimate chlorophyll levels. Readings were taken from the youngest, most recently mature leaf. Data combined for 2018 and 2019. Mixed linear regression model used to compare treatment means (p-value = 0.33).

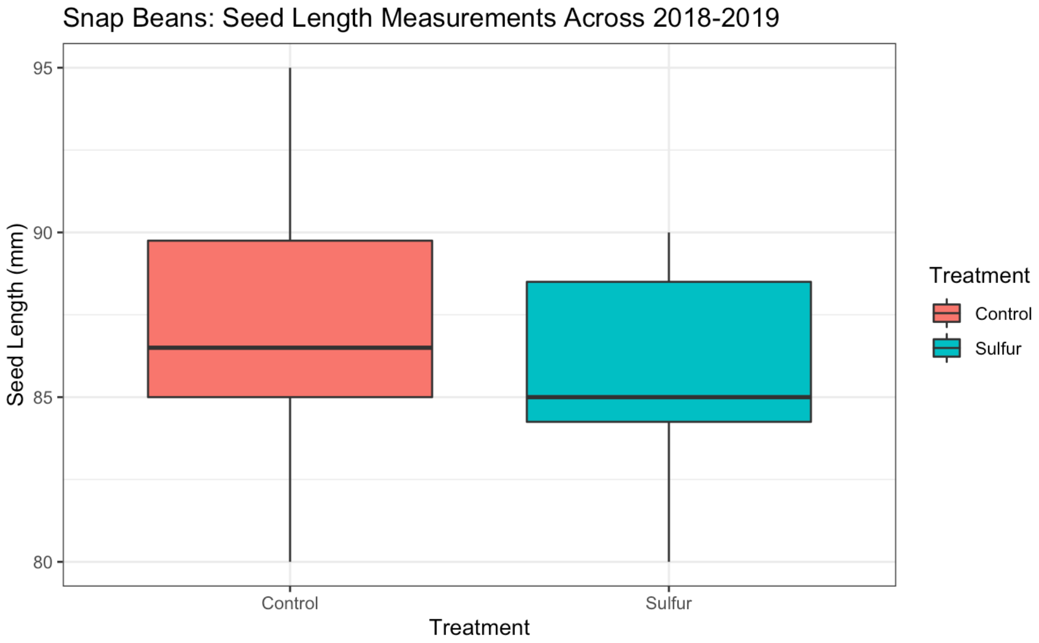

Figure 9: After the test plots are harvested and run through the grading machine, for each replication, we randomly select 10, 4 sieve beans for seed measurements. One seed is taken from each bean and the total length of 10 seeds measured. Snap bean seed length comparison across treatments, in mm, of 4-sieve pods. Data for 2018 and 2019 combined. Linear regression model used to compare treatment means (p-value = 0.49).

Of the crops evaluated, snap beans appeared least responsive to S addition. The fields used for snap beans had soil S levels of 5 and 3.6 ppm. As with peas, our trial showed a critical level of 8 ppm was too high. At this time, based on the finding of this study, S supplementation is not recommended for snap bean production on fine textured soils in New York.

Sweet corn, although not statistically affected by gypsum application, did show trends of S potentially impacting husked ear weight and ear length. Preseason soil samples, taken April 25th in 2018 and May 10th in 2019, resulted in readings of 4.2 ppm and 23.2 ppm, respectively. This reading was much higher than any other field tested so the sample was re-run with a similar outcome. A late season sample taken in the field August 21, 2019, resulted in a reading of 2.5 ppm. No other samples taken from the Cornell AgriTech fields had a reading as high as 23.2 ppm and it remains an unexplained outlier. Pre-husked yield showed no significant difference between treatments with a p-value of 0.43 (Figure 10). Husked weight comparisons showed no statistical differences but was trending towards a positive impact with S addition with a p-value of 0.23 (Figure 11). Similarly, figure 12 shows that treatment had no significant impact on ear length, but S treatment was potentially positively impacting ear length in certain scenarios (p=0.14). Ear butt diameters and SPAD readings showed no statistical difference between treatments (Figure 13 and 14).

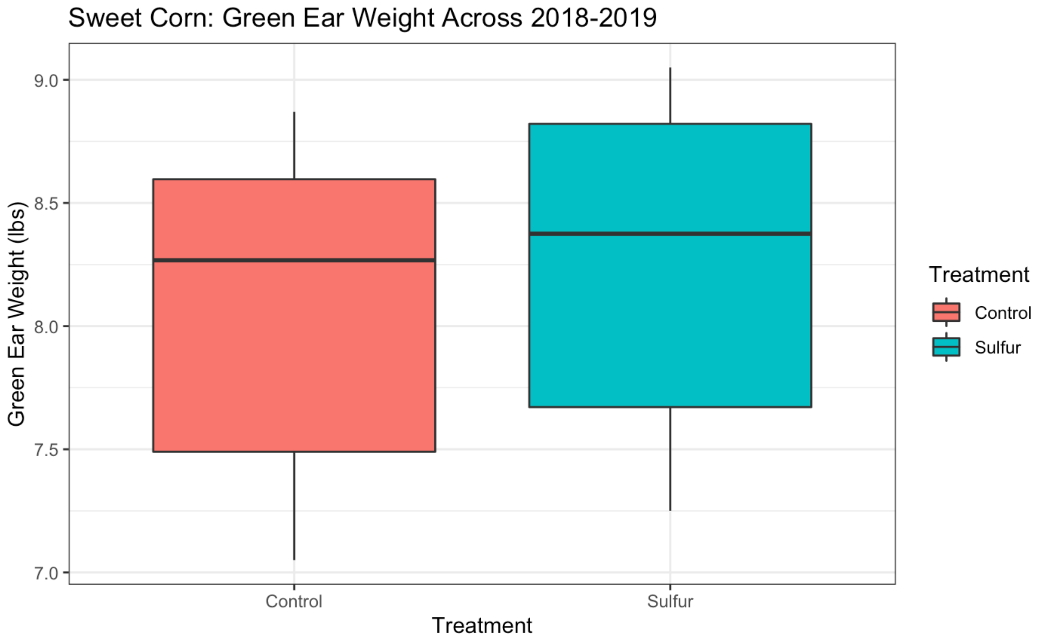

Figure 10: Green ear weight is the weight of ears from a randomized harvest of 10 ears, data is recorded separately from each of the 5 reps, for both the control and S treatments. Data combined for 2018 and 2019. Linear regression model used to compare treatment means (p-value = 0.43).

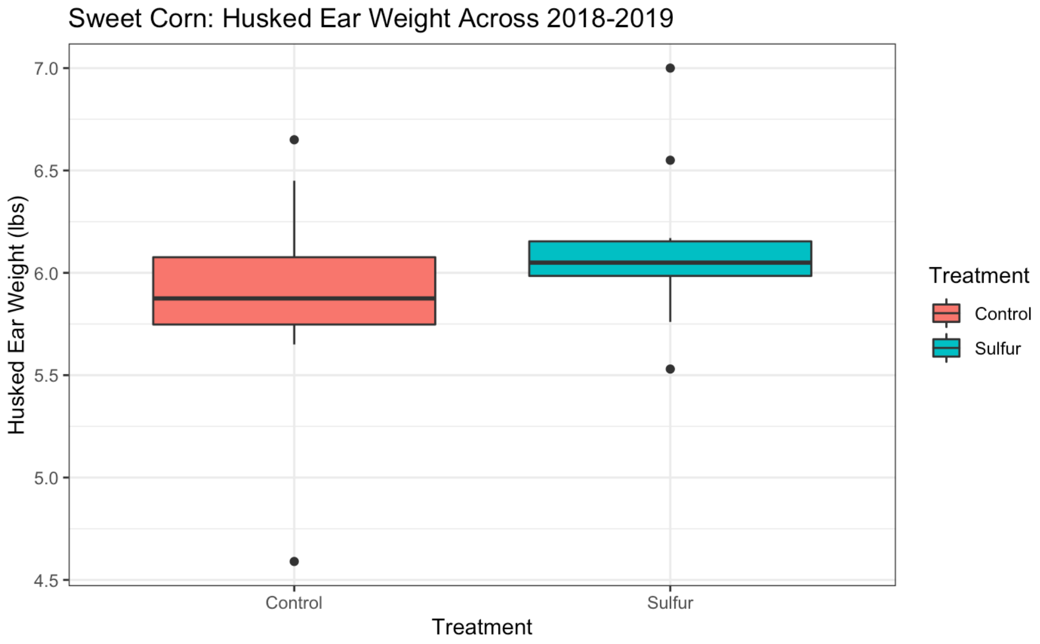

Figure 11: After 10 ears are randomly harvested from each of the 5 reps, for both the control and S treatments, and green ear weight is recorded, the ears are hand husked and weighed. Data combined for 2018 and 2019. Linear regression model used to compare treatment means (p-value = 0.23).

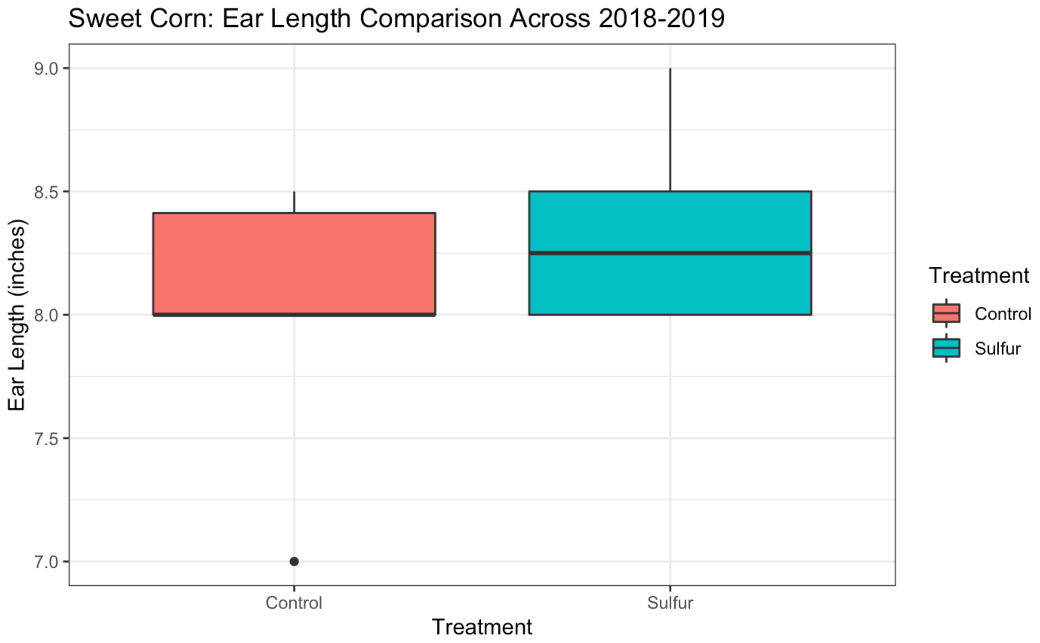

Figure 12: Length is measured for each treatment, from our sample of 10 ears for each of the 5 replications separately. Data combined for 2018 and 2019. Linear regression model used to compare treatment means (p-value = 0.14).

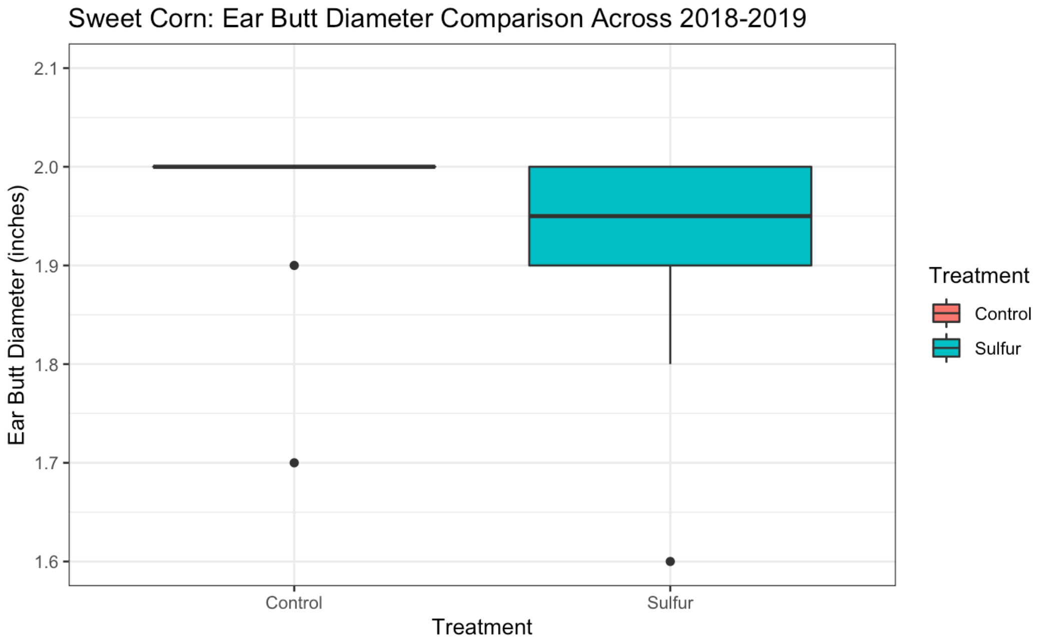

Figure 13: Ear butt diameter measurement was taken with calipers at the base end of the husked ear. Measurements were taken from the same 10 ears used for green weight and husked weight. Each replication was measured separately. Data combined for 2018 and 2019. Linear regression model used to compare treatment means (p-value = 0.32).

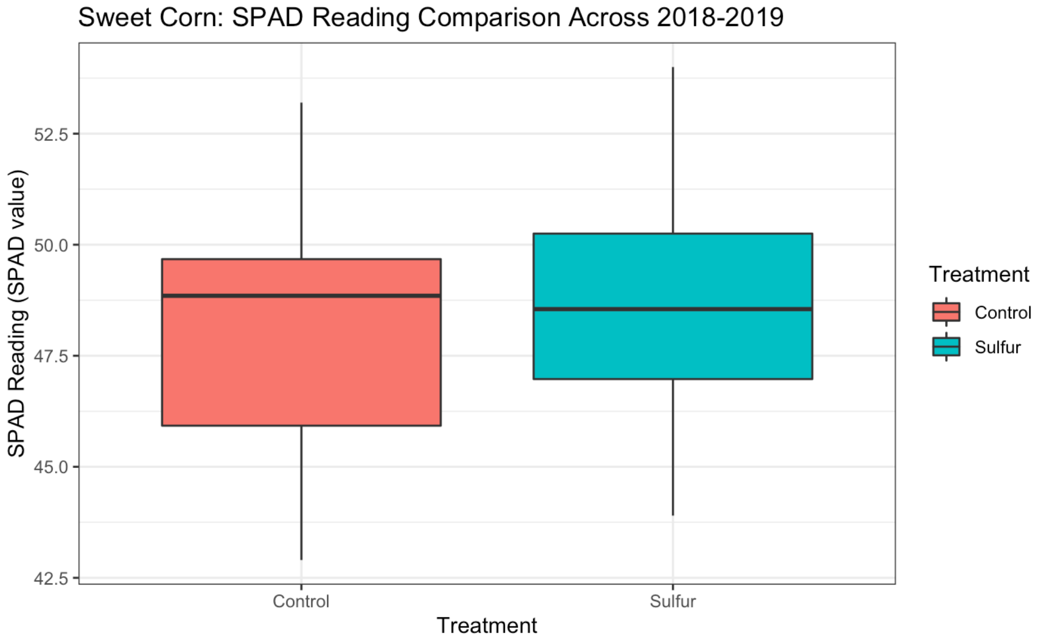

Figure 14: SPAD readings were taken three weeks before harvest and use a greenness measurement to estimate chlorophyll levels. Readings were taken from the youngest, most recently mature leaf. 5 replications for control and S treatment were measured separately. Data combined for 2018 and 2019. Linear regression model used to compare treatment means (p-value = 0.44).

Several researchers across the United States have shown field and sweet corn crops response to S fertilization (Brust 2018, Kim et al. 2012, & Sawyer et al. 2011). Many experiments that have shown a positive impact of S addition to corn have been in areas with course textured soils (Kaiser & Vetsch 2019; Laboski & Peters 2012; and Camberato & Casteel 2017). Our sweet corn trials were conducted on fine textured soils, specifically Honeoye loam and Lima loam. Our trial suggested that sweet corn grown on fields with fine textured soils in New York does not benefit from S addition. As with the other processing crops in this study, the critical soil test S value is lower than the 8 ppm determined for alfalfa. More works needs to be done to identify soil S threshold for specific crops, soil types and timing of soil testing.

Conclusions:

None of the three processing crops trialed here showed a statistically significant response to gypsum as an S source. All the trials were conducted on fine textured soils with soil test S levels at or below 8 ppm. This showed that the critical soil test S levels for such soils is lower than 8 ppm and that future research should focus on coarse textured soils with higher risk for S deficiencies. The soil test S threshold levels will likely differ between fine textured soils and coarse textured soils. At this time, our trials indicate growers with fine textured soils do not need to add gypsum when growing English peas, snap beans or sweet corn. However, if the trend of decreasing atmospheric S deposition continues, S deficiencies may occur more often in future years and monitoring of S status and needs of all crops will be needed.

WORKS CITED

Brust, J. (2018). Sulfur Deficiency in Sweet Corn. https://sites.udel.edu/weeklycropupdate/?p=12411

Brust, J. (2019). Sulfur Deficiency in Sweet Cron and Watermelons. https://sites.udel.edu/weeklycropupdate/?p=13894

Camberato, J., & Casteel, S. (2017). Soil Fertility Update: Sulfur Deficiency. https://www.agry.purdue.edu/ext/corn/news/timeless/sulfurdeficiency.pdf

Chao, T.T., Harward, M.E., & Fang S.C. (1962). Movement of S35 Tagged Sulfate Through Soil Columns. Soil Science of America Journal, 26(1), 27-32. https://doi.org/10.2136/sssaj1962.03615995002600010008x

Environmental Protection Agency. (2019). Progress Report: Acid Deposition. https://www3.epa.gov/airmarkets/progress/reports/acid_deposition_figures.html#figure3

Gatiboni, L., & Hardy, D. (2019). Sulfur Fertilization of North Carolina Crops. https://content.ces.ncsu.edu/sulfur-fertilization-of-north-carolina-crops

Heckman, J. (2021). Sulfur Nutrition and Soil Fertility Management for New Jersey Crops. https://njaes.rutgers.edu/e365/

Kaiser, D.E., & Vetsch, J.A. (2019). Sulfur for Minnesota Soils. https://extension.umn.edu/micro-and-secondary-macronutrients/sulfur-minnesota-soils

Kim, K., Kaiser, D.E., & Lamb, J. (2012). Corn Response to Starter Fertilizer and Broadcast Sulfur Evaluated Using Strip Trials. American Society of Agronomy, 105(2), 401-411. https://doi.org/10.2134/agronj2012.0299

Ketterings, Q.M., Godwin, G., Gami, S., Dietzel, K., Lawrence, J., Barney, P., Klicer, T., Stanyard, M., Albers, C., Cherney, J.H., Cherney, D., & Czymmek, K.J. (2012). Soil and Tissue Testing for Sulfur Management of Alfalfa in New York State. Soil Science Society of American Journal, 76(1), 298-306. https://doi.org/10.2136/sssaj2010.0437

Laboski, C.A.M., & Peters, J.B. (2012). Nutrient Application Guideline for Field, Vegetable, and Fruit Crops in Wisconsin. https://walworth.extension.wisc.edu/files/2018/11/Nutrient-Application-Guidelines-for-Field-Vegetable-Fruit-Crops-in-WI-A2809.pdf

Marschner, P. (2012). Marschner's Mineral Nutrition of Higher Plants. Academic Press. https://doi.org/10.1016/C2009-0-63043-9

Reiners, S., Curtis, P.D., Helms, M., McGrath, M.T., Nault, B.A., & Seaman, A. (2019). 2019 Cornell Integrated Crop and Pest Management Guidelines for Commercial Vegetable Production. Cornell University.

Sawyer, S., Lang, B., & Barker, D. (2011). Sulfur Fertilization Response in Iowa Corn Production. International Plant Nutrition Institute, 95(2), 8-10.Retrieved from http://www.ipni.net/publication/bettercrops.nsf/0/29F78D57A92A19C68525797C0076D040/$FILE/Better%20Crops%202011-2%20(lo%20res).pdf

United States Department of Agriculture (USDA). (2020). Honeoye Series. https://soilseries.sc.egov.usda.gov/OSD_Docs/H/HONEOYE.html

United States Department of Agriculture (USDA). (2011). Lima Series.

https://soilseries.sc.egov.usda.gov/OSD_Docs/L/LIMA.html

United States Department of Agriculture-National Agricultural Statistics Service (USDA NASS). (2018). 2018 State Agriculture Review. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEW%20YORK

United States Department of Agriculture-National Agricultural Statistics Service (USDA NASS). (2017.) 2017 Census of Agriculture – State Data. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_2_US_State_Level/st99_2_0029_0029.pdf

CHAPTER 3

Gypsum as a Potential Sulfur Supplement for Field Tomato Production in New York

Abstract:

Continually decreasing trends of atmospheric deposition of sulfur (S), reduced manure usage in vegetable production systems, and increased use of S-free fertilizer, lead to the hypothesis that supplemental S could benefit tomato crops. Tomatoes (*Solanum lycopersicum L.*), botanically a fruit, takes up relatively large amounts of nutrients, including S. Here we test the impact of S addition using gypsum on tomato yield as well as fruit quality aspects, mainly higher soluble solids and titratable acids. Gypsum was chosen as a S source because it is relatively inexpensive, can be mined or produced, and can be used in certified organic systems. Trials were conducted in 2018 and 2019, using gypsum equaling 68 kg of sulfate per ha, to determine if S was limiting yield or impacting quality. Metrics measured included: total yield, extra-large fruit, soluble solids, titratable acids, foliar S content and taste. A discriminative, paired comparison test (n=100) was conducted with the Cornell Sensory Evaluation Center and revealed no significant differences in consumer perception of sweetness, acidity, or ideal tomato flavor. There were no statistically significant differences between S treated plots and untreated control plots for any of the parameters measured. These results suggest that S addition is not needed for tomatoes grown on fine textured soil, but additional work is needed on a range of soil types in future years.

Introduction:

Historically, sulfur (S) has been plentiful in soils and inadvertently supplied to crops via atmospheric deposition, manure usage, and as by-products in commercial fertilizers. Environmental regulations over the past 50 years have drastically reduced atmospheric deposition of S into soils. Further, manure usage on vegetable farms has decreased over the past century and most commonly used fertilizer for phosphorus (P) no longer contains S as a byproduct. These changes have all led to reduced S being deposited into soils and have increased the possibilities of a S deficiency for crop production. In 2012, Ketterings et al. (2012), identified 8-ppm soil sulfur level, using the Cornell Sulfur Test, as a minimum threshold for alfalfa in New York, with samples taken at second cutting. Research is needed to evaluate if this critical soil test S level can be used for other crops. Tomatoes were chosen as a test crop because they are widely grown across New York, it takes up relatively large quantities of nutrients, contain higher soluble solids and titratable acids than many other crops, and is a crop for which flavor is highly valued by customers.

In 2017, New York ranked 12th in field tomato production acreage across the United States, with about 770 ha of field tomatoes harvested (USDA NASS 2017). Although tomatoes are not a major crop in New York based on land area; they are almost ubiquitous across small to regionally sized farms in the state. Furthermore, tomatoes remain very popular at farmers' markets.

Although valued for their flavor, there is also a societal consensus that grocery store tomatoes are bland with an overall decrease in flavor compared to years ago. Researchers have been looking into this topic (Powell et al. 2012; Tieman et al. 2017; Goa et al. 2019). In the past, breeding for many vegetable varieties was predominately focused on yield, shelf-life, and pathogen resistance. Strict focus on these attributes is believed to have had an impact on tomato quality over the years and have potentially impacted flavor (Powell et al. 2012; Tieman et al. 2017; Goa et al. 2019). Over the past decade, focus on yield, shelf-life and pathogen resistance has remained, but more attention has been given to improving flavor as well. Newer tomato varieties like, 'Damsel', a modern hybrid with high yields and pathogen resistance, is also advertised as having heirloom "quality and flavor" (https://www.highmowingseeds.com/organic-non-gmo-damsel-f1-tomato.html). Although varieties like 'Damsel' have higher quality, large chain stores would likely not have a 'Damsel' type tomato or just a limited quantity for a premium price. The prototypical, large, uniform, beefsteak type tomatoes that ship well still dominate the market. Based on communication with several extension educators and growers across New York, we decided to use 'Red Deuce' as our test variety to best emulate a New York grown tomato that might be offered in a grocery store, and test whether decreased soil S levels are impacting tomato yield, size, and taste.

Flavor is a complex concept, generally described as both aroma and taste stimuli, and their interactions with each other, as well as an individual's unique processing of the stimuli (Heyman et al. 1993, Perez and Sanz 2008). Taste refers to oral sensations perceived via gustatory receptors located on the tongue, and aroma to volatile compounds experienced via olfactory receptors (Heyman et al. 1993; Molnar & Gair 2015). When consuming food, humans experience aroma and taste at the same time, creating a synergistic or antagonistic experience. For our study, we focused on basic measurements of soluble solids and titratable acids for quality metrics, thus focusing on the taste. Soluble solids and titratable acids are responsible for much of our experience of taste when it comes to fruit (Perez & Sanz 2008) and fit better into the scope of this project as the role of S in plants could make it possible for S deficiencies to decrease yield as well as soluble solids and titratable acids.

Sulfur is a constituent of amino acids, proteins, and other important compounds (Marschner 2012). Notably, sulfur is a constituent of plant chloroplasts and iron-sulfur clusters, both of which are crucial for the process of photosynthesis (Przybyla-Toscano et al. 2018, Qian et al. 2020). Reductions in photosynthesis could cause an overall decrease in yield, as well as carbohydrate production, and in turn soluble solids. Further, N nutrition in plants has been linked to differences in titratable acids in fruit, and synergism has been described between S and N uptake in the literature (Marschner 2012; Liao et al. 2019; Qian et al. 2020). Therefore, the literature illustrates the possibility of S, as well as imbalances with N, as potentially impacting soluble solids and titratable acid levels in fruits.

Although mostly out of the scope of our work, many secondary S compounds are potential aroma stimuli. For example, if sulfur is a limiting nutrient in cruciferous vegetable production, they will lack high levels of glucosinolates, which are responsible for a distinct crucifer aroma (Higdon et al. 2005). To test flavor, both taste and smell together, we originally planned a Triangle Test for our sensory evaluation. Triangle Tests are a common starting point for researchers to test if products are identifiably different to consumer panels (Rodgers 2017). Like the reasoning behind our high fertilizer rate for this study, we wanted to conduct preliminary research to test for flavor differences and see if future research was warranted. If our tests indicated a difference, then further HPLC work and sensory panels could be run to further illuminate the differences. Unfortunately, ripening was an issue for our scheduled sensory evaluation the first year of trials, and we switched to a discriminative, paired comparison test, replicated twice. This allowed us to proceed with a sensory evaluation and ensure enough samples for our goal of n=100.

Our objectives were to test if S deficiency was impacting field tomato production and if supplemental S could increase yield and quality. We hypothesized that gypsum is a cheap, sustainable, supplemental S source for tomatoes that can increase yield, quality and taste via increased soluble solids and titratable acids, where S is limiting.

Materials and Methods:

Trials were conducted at Cornell AgriTech in Geneva NY in 2018 and 2019. Both years the seeds were started in 72 cell trays, with Cornell mix growing medium, in greenhouses at the Cornell AgriTech campus, 6-8 weeks before transplant. Greenhouse temperatures were set for 24 degrees Celsius daytime and 15.5 degrees Celsius for night. Trays were watered as needed. At about 3 to 4 weeks seedlings were fertilized with 20-20-20 at a rate of about 1.0 gram to one liter of water, providing approximately 200 ppm, 87 ppm, and 167 ppm, of N, P and K respectively. One week before transplanting the trays were placed in cold frames to be hardened off.

Soil samples, taken in spring of 2018 at a depth of 0-20 cm showed a 0.01 M $CaCl_2$ extractable soil S level of 6.1 ppm. In 2019 samples were taken in spring and fall, resulting in 5 ppm and 3.8 ppm, respectively. The field the tomatoes were planted in was conventionally tilled. The ground was chisel plowed and disked until the consistency was ideal for laying plastic mulch. Plots were 0.76 m wide and 6.1 m in length and each treatment was replicated six times using a complete randomized block design. Gypsum was hand applied at a rate that supplied 68 kg ha^{-1} of sulfate in the treatment plots. Directly after fertilization, plastic mulch and drip irrigation were laid on 1.8 m centers. The plots were then marked with wooden stakes to identify plots. Tomato transplants were planted in a single row at 0.6 m in row spacing, equaling 10 plants per plot. After planting, plants were hand watered with 250 ml solution of a 20-20-20 fertilizer at a rate of about 0.25 grams to one liter of water, providing approximately 50 ppm, 22 ppm, and 42 ppm of N, P and K respectively. Plots were watered twice a week depending on rainfall, 1.27 cm of water per watering, totaling 2.54 cm per week. Plots were additionally fertilized according to soil tests and the Cornell guidelines for commercial vegetable production (Reiners et al. 2019). Plants were transplanted by hand and planted on 6/12 in 2018 and 6/09 in 2019. Rows were staked and tomatoes were trellised using the “Stake and Weave” or “Florida Weave” method (Nitzsche 2009). A foliar tissue sample was taken during flowering for both 2018 and 2019. Three leaves from each rep were collected from the youngest mature leaf. Leaves were put in a drying oven at 54 Celsius until dry and then crushed by hand with a mortar and pestle. Samples were analyzed by the Cornell Nutrient Analysis Laboratory in Ithaca, NY determining S ppm.

Harvest began when fruit changed from dark/light green to yellow/red and occurred weekly for 4 weeks. Peak production was estimated to be around weeks two to three of harvest and a sensory test was set to occur during peak production, to ensure sufficient product for testing. Harvest was taken from the eight interior plants, the two outermost plants acting as a guard. Total weight was recorded, then fruit was examined for culls and weighed. Fruit was graded by hand to split yield into USDA grades: small (5.4 to 5.7 cm), medium (5.7 to 6.4 cm), large (6.4 to 7 cm), and extra-large (>7 cm), and weight was recorded from each category (USDA 1991).

For soluble solids and titratable acid testing, we took three USDA ‘large’ fruits from each replication, juiced them using a small hand powered grape press, and labeled them accordingly. Juice from each replication was tested for a brix value using a Misco refractometer and titratable acid value using a Metrohm 848 Titrino plus. From the same harvest, the rest of the ripe, large fruits, were transported to Ithaca NY, where sensory evaluations were held in the Sensory Evaluation Center in Stocking Hall, on Cornell campus. For our sensory evaluations, n=100 was our goal, and we accomplished this by utilizing a diverse mailing list created by the Evaluation Center for Sensory Research, which is comprised of students, faculty, and staff, as well as local participants from the Ithaca community. Out of the total 200 participants, from 2018 and 2019, 148 were females and 52 males, they ranged in age from 18 to 71, with 150 participants being in the 18 to 35 range. 12 participants reported eating tomatoes daily, 65 a few times a week, 63 once a week, 41 once in the last two weeks, 16 in the last month and 3 in the last 3 months. Participants were asked to sign up for timeslots in an 8-hour time period where they would taste tomatoes. The evaluation was a discriminative, paired comparison test, where participants were asked to taste two randomly numbered samples, and determine which sample was sweeter, which more acidic, and which had the more ideal tomato flavor. Individual tomatoes were chosen to avoid, as far as possible, variation in size and ripeness of samples to be compared. Tomatoes were cut into eighths to create a uniform wedge being served to participants. Participants checked in and were assigned a booth number, where they sat down and entered demographic information into a computer. Participants were then served their first sample, presented with the three questions and asked to cleanse their palate with water and a cracker. The participants were then provided with the second sample and asked the same set of questions. Answers were entered into a computer with RedJade software, which compiled data.

Data from the trials were analyzed using RStudio software and in cooperation with the Cornell Statistical Consulting Unit. Linear and Mixed linear models were used with an alpha value of 0.05.

Results, Discussion, Graphs and Tables:

From both the 2018 and 2019 trials, there were no statistically significant results indicating differences between S treated and untreated control plots, in the categories of total yield (p=0.58) (Figure 1), extra-large fruit (p=0.38) (Figure 2), soluble solids (p=0.81) (Figure 3), titratable acids (p=0.80) (Figure 4), and foliar S content (p=0.52) (Figure 5). Furthermore, our sensory evaluation data showed no strong trends or consumer panelist recognition of differences in S treated and control plot tomato samples (Tables 1 and 2). Data from 2018 and 2019 showed that 84 out of the 200 participants chose different treatments for the question, "which sample is sweeter". Out of the 116 participants who were consistent, 63 answered the control samples were sweeter and 53 answered the sulfur treatment samples were sweeter. For the question, "which sample was more acidic", 97 of 200 participants did not answer the question consistently for replications 1 and 2. Out of the 103 participants who answered consistently, 36 answered the control samples were more acidic and 67 that the S treated tomatoes were more acidic. Although half the participants did not consistently identify the treatments, this last question was the only one that showed any possible trend. As mentioned above, we measured the titratable acids from both treatments, and there were no statistically significant results with a p-value of 0.80. However, both years of the trial, titratable acid level means were slightly higher in the S treated tomatoes. Additional research is needed but there could be a potential aroma stimulus making participants think the S treated tomatoes tasted more acidic, or perhaps the S treated tomatoes did contain more acid in some scenarios. Our last question, "which sample has ideal tomato flavor", similarly had 96 out of 200 participants answer differently for replications 1 and 2. Out of the 104 participants who answered consistently, 50 thought the control samples displayed ideal flavor, and 54 thought the sulfur treated tomatoes displayed ideal tomato flavor. All our results indicate that the fields used in 2018 and 2019 had sufficient soil S levels for tomato production in our trials. As our soil samples recorded for the tomato trials were below the 8-ppm threshold for alfalfa at second cutting (Ketterings et al. 2012), we conclude the critical soil S level is lower than 8 ppm and additional research is needed to set a critical level.

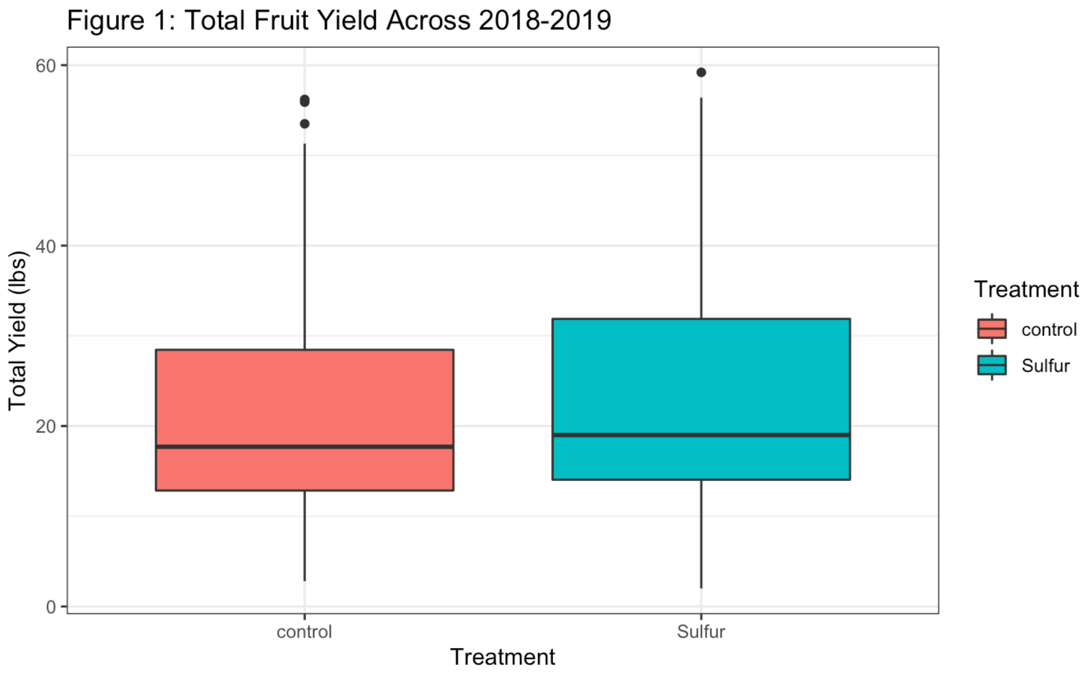

Figure 1: Six control test plots and six S treated plots, each consisting of 10 plants, were harvested once a week for four weeks. Harvest was taken from the 8 interior plants, leaving one plant on each end of the replication to act as a guard. Total fruit yield shows the mean yield across all replications and across 2018 and 2019. Mixed linear regression model used to compare treatment means (p-value = 0.58).

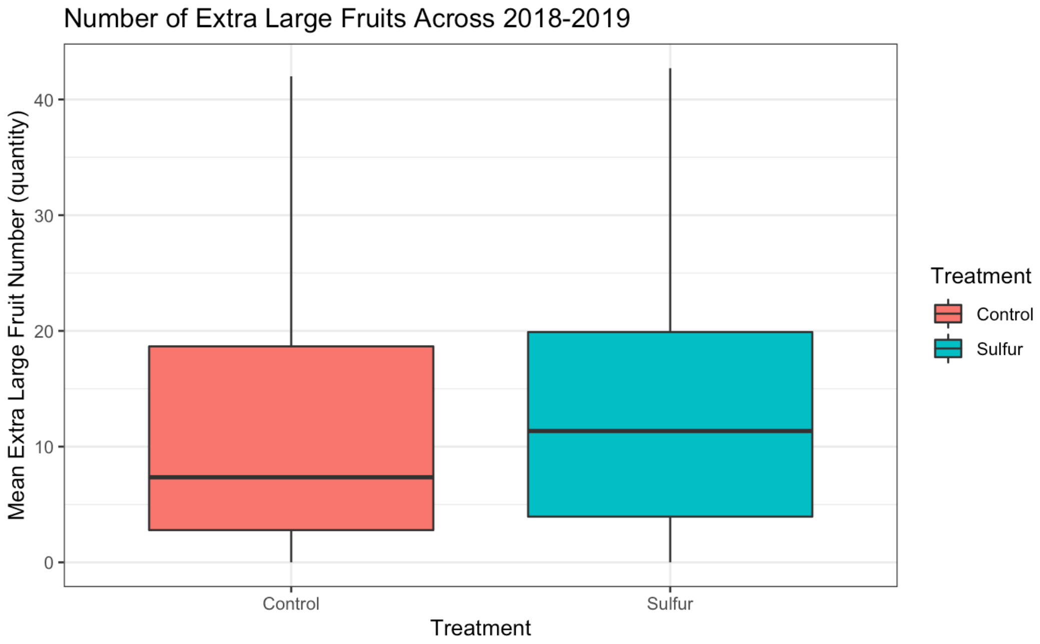

Figure 2: Six control test plots and six S treated plots, each consisting of 10 plants, were harvested once a week for four weeks. Harvest was taken from the 8 interior plants, leaving one plant on each end of the replication to act as a guard. This graph shows the mean number of extra-large fruits (fruits greater than 7 cm in diameter) across all replications, from both 2018 and 2019. Mixed linear regression model used to compare treatment means (p-value = 0.38).

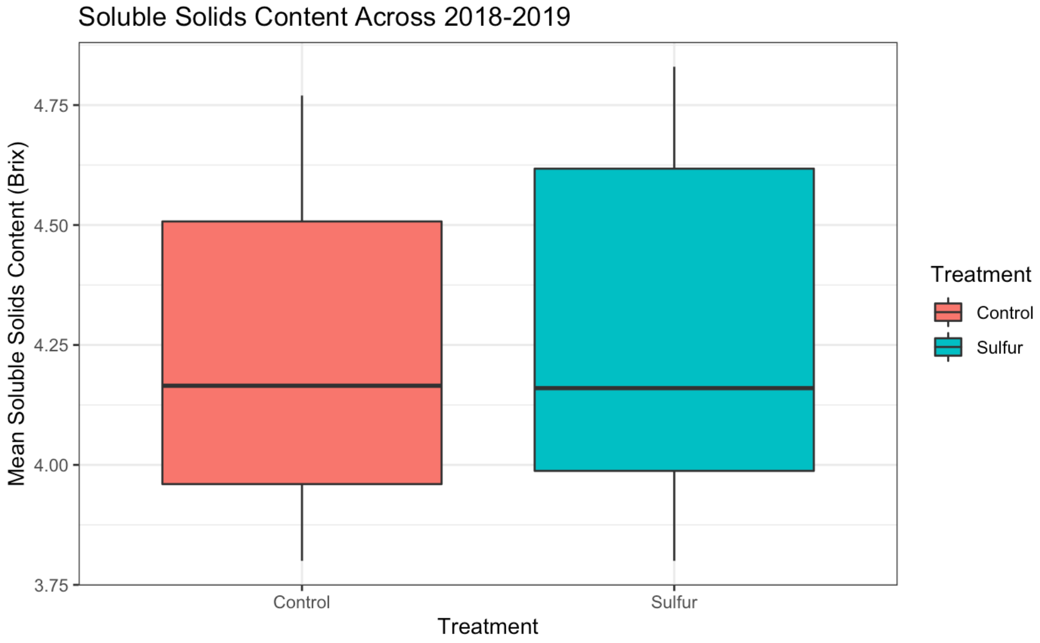

Figure 3: Six control test plots and six S treated plots, each consisting of 10 plants, were harvested for four weeks, weeks two to three considered peak harvest. Harvest was taken from the 8 interior plants, leaving one plant on each end of the replication to act as a guard. At peak harvest, three large fruit (6.4 to 7 cm) were taken from each replication and juiced using a hand powered grape press. Juice was tested for brix using a Misco refractometer. Data for 2018 and 2019 combined. Linear regression model used to compare treatment means (p-value = 0.81).

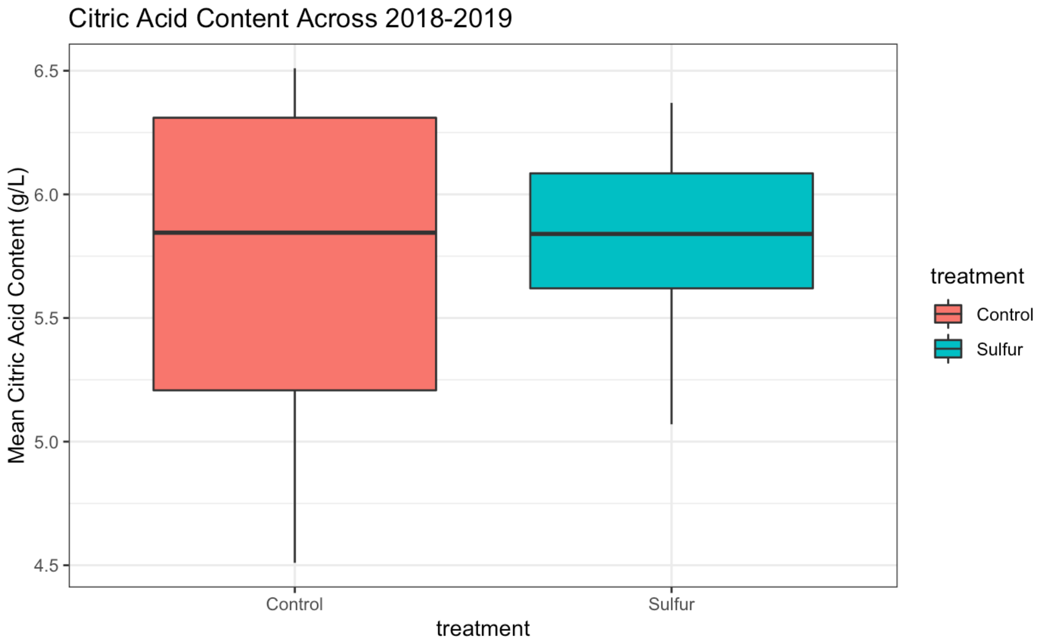

Figure 4: Six control test plots and six S treated plots, each consisting of 10 plants, were harvested for four weeks, weeks two to three considered peak harvest. Harvest was taken from the 8 interior plants, leaving one plant on each end of the replication to act as a guard. Three large fruit (6.4 to 7 cm) were taken from each replication and juiced using a hand powered grape press. Juice was tested for titratable acids using a Metrohm 848 Titrino plus. Data for 2018 and 2019 combined. Linear regression model used to compare treatment means (p-value = 0.80).

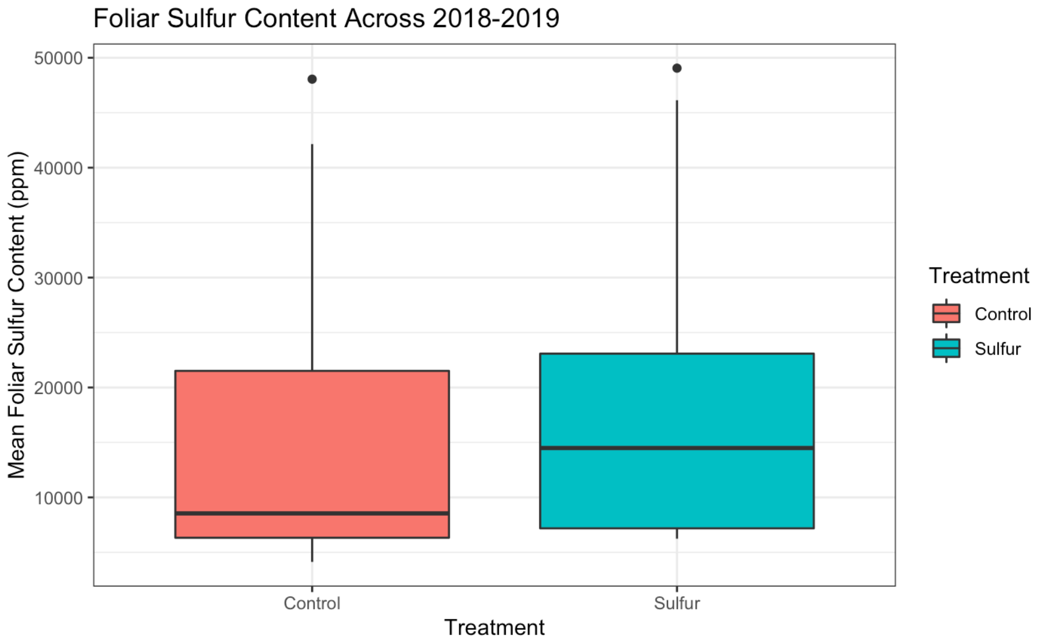

Figure 5: At flowering, three randomly selected foliar samples were taken from each of the six control and six S treated replications. Foliar samples were taken from the youngest mature leaf, dried in an oven at 54 Celsius until dry, hand ground with a mortar and pestle and sent to CNAL and S content was measured in parts per million. Data for 2018 and 2019 combined. Linear regression model used to compare treatment means (p-value = 0.52).

Table 1: Consumer panelists were asked to eat two randomly numbered tomato samples side-by-side, one containing an S treated tomato, and one containing a control tomato, and answer three questions, which sample is sweeter, which sample is more acidic and which sample has ideal tomato flavor. This process was replicated twice. The results below show which participants answered questions from replication 1 and 2 accurately or inaccurately.

Sensory Evaluation 2018 and 2019 Consistency Results			
	Sweetness	Acidity	Ideal Flavor
Reps 1+2 inconsistent	84	97	96
Reps 1+2 match	116	103	104

Table 2: Consumer panelists were asked to eat two randomly numbered tomato samples side-by-side, one containing an S treated tomato, and one containing a control tomato, and answer three questions, which sample is sweeter, which sample is more acidic and which sample has ideal tomato flavor. This process was replicated twice. Results show preference for participants who answered replication 1 and 2 consistently.

Sensory Evaluation 2018 and 2019 Preference Results			
	Sweetness	Acidity	Ideal Flavor
Control treatment	63	36	50
Sulfur treatment	53	67	54

Conclusions:

The results of these trials suggest addition of S is not needed for tomatoes grown on fine textures soils with moderate to high organic matter. Continually decreasing trends of atmospheric deposition of S, reduced manure usage for vegetable production, and S free P fertilizers can cause S deficiencies in future years. Further monitoring and research will be required to develop critical soil test S levels for tomatoes so that deficiencies can be detected in future years.

WORKS CITED

Brust, J. (2018). Sulfur Deficiency in Sweet Corn. https://sites.udel.edu/weeklycropupdate/?p=12411

Gao, L., Gonda, I., Sun, H., et al. (2019). The tomato pan-genome uncovers new genes and a rare allele regulating fruit flavor. Nat Genet, 51(6), 1044-1051. https://doi.org/10.1038/s41588-019-0410-2

Heyman, H., Holt, L.D., & Cliff, M.A. (1993). Measurement of flavor by sensory descriptive techniques. IN: Ho, C., -T & Manley, C.H. (eds), Flavor Measurement, Chap. 6, 113-131. Retrieved from https://www.researchgate.net/publication/271838181_Measurement_of_Flavor_by_Sensory_Descriptive_Techniques

Higdon, J., Drake, V.J., Delage, B., & Traka, M. (2005). Cruciferous Vegetables. https://lpi.oregonstate.edu/mic/food-beverages/cruciferous-vegetables

Johnson, G., (2018). Sulfur and Vegetable Crops. https://sites.udel.edu/weeklycropupdate/?p=12050

Ketterings, Q.M., Godwin, G., Gami, S., Dietzel, K., Lawrence, J., Barney, P., Klicer, T., Stanyard, M., Albers, C., Cherney, J.H., Cherney, D., & Czymmek, K.J. (2012). Soil and Tissue Testing for Sulfur Management of Alfalfa in New York State. Soil Science Society of American Journal, 76(1), 298-306. https://doi.org/10.2136/sssaj2010.0437

Liao, L., Dong, T., Qui, X., Rong, Y., & Wang, Z. (2019). Nitrogen Nutrition is a key modulator of sugar and organic acid content in citrus fruit. PLOS ONE 14(10): e0223356. https://doi.org/10.1371/journal.pone.0223356

Molnar, C., & Gair, J. (2015). Concepts of biology – 1st Canadian Edition. BC campus:OpenEd. https://opentextbc.ca/biology/

Nitzsche, P., Kline, W., Infante-Casella, M., & Maletta, M. (2009). The Stake and Weave Training System for Tomatoes in the Home Garden. https://njaes.rutgers.edu/FS1102/

Noble, A.C., (1996). Taste – aroma interactions. Trends in Food Science & Technology, 7(12). 439-444. https://doi.org/10.1016/S0924-2244(96)10044-3

Powell, A.L., Nguyen, C.V., Hill, T., Cheng, K.L., Figueroa-Balderas, R., Aktas, H., Ashrafi, H., Pons, C., Fernadez-Munoz, R., & Bennet, A.B. (2012). Uniform ripening Encodes a Golden 2-like Transcription Factor Regulating Tomato Fruit Chloroplast Development. Science,(6089). 1711-1715. https://doi.org/10.1126/science.1222218

Rodgers, L. (2017). Discrimination Testing in Sensory Science: A Practical Handbook. Woodhead Publishing, an imprint of Elsevier. https://www.sciencedirect.com/book/9780081010099/discrimination-testing-in-sensory-science#book-description

Perez, A.G., & Sanz, C. (2008). Formation of fruit flavour. Bruckner, B., and Wylie, S.G. (eds.), Fruit and vegetable flavour. Pgs. 41-60. Woodhead Publishing. Retrieved from https://ubblab.weebly.com/uploads/4/7/4/6/47469791/fruit_&_vegetable_flavour;_recent_advances_&_future_prospects.pdf

Przybyla-Toscano, J., Boussardon, C., Law, S.R., Rouhier, N., & Keech, O. (2021). Gene atlas of iron-containing proteins in Arabidopsis thaliana. The Plant Journal, 106(1). 258-274. https://doi.org/10.1111/tpj.15154

Qian, L., Goa, Y., Yang, A. 2020. Sulfur Homeostasis in Plants. International Journal of Molecular Sciences, 21(23): 8926. https://doi.org//10.3390/ijms21238926

Tieman, D., Zhu, G., Resende, M.F.R., Lin, T., Nguyen, C., Bies, D., Rambla, J.L., Beltran, K.S.O., Taylor, M., Zhang, B., Ikeda, H., Liu, Z., Fisher, J., Zemach, I., Monforte, A., Zamir, D., Granell, A., Kirst, M., Huang, S., & Klee, H. (2017). A Chemical Genetic Roadmap to Improved Tomato Flavor. Science, 355(6323), 391-394. https://doi.org/10.1126/science.aal1556

United States Department of Agriculture-Agricultural Marketing Service (USDA AMS). (1991). United States Standards for Grades of Fresh Tomatoes. https://www.ams.usda.gov/sites/default/files/media/Tomato_Standard%5B1%5D.pdf

United States Department of Agriculture: National Agriculture Statistics Service (USDA NASS). (2017). 2017 Census of Agriculture – State Data: New York. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_State_Level/New_York/st36_1_0036_0036.pdf