ABSTRACT

KILE, LILY KATHARINE. The Influence of Winter Cover Crops and Fertilizer Application on Nutrient Uptake and Yield Response in Sweet Potato (*Ipomoea batatas*) Production (Under the direction of Dr. Alex Woodley).

Two studies were conducted to evaluate nutrient dynamics in the soil, plant tissue, and yield responses in sweet potato production. The first study evaluated the use of polyhalite as a source of potassium fertilizer for sweet potato compared to the more commonly used Muriate of Potash (MOP). The rates for MOP and polyhalite were 0, 32.5, 62, 126, and 188 kg K ha^{-1}. The other treatments also included a control with no added fertilizers, a control for nitrogen, and a control for nitrogen and sulfur. A MOP and Ca, Mg, S treatment was included to examine the impact of these nutrients within polyhalite. A regression analysis showed a statistically significant quadratic response to fertilizer application regardless of source. The distributions of grades among treatments varied. Higher rates of polyhalite treatments produced a higher proportion by total weight of jumbos and a smaller proportion of canners when compared to the control. Soil samples showed that MOP initially released a higher amount of potassium than polyhalite. However, the amount of potassium sustained in the soil by the end of the season was equal between treatments when initial K levels were low. These findings suggest that polyhalite can be a useful source of potassium and its use will result in comparable yield responses to the MOP. The second study evaluates three different cover crops for their effectiveness at managing nutrients for organic sweet potato production. The cover crops included were cereal rye (*Secale cereale*), crimson clover (*Trifolium incarnatum*), and Austrian winter pea (*Pisum sativum*). Over-winter fallow plots were also used to compare cover crop treatments with sodium nitrate applied at 0, 20, 40, 60, 80, and 120 kg N ha^{-1}, allowing a fertilizer equivalency estimate. Soil data showed that there were no differences in N among any of the cover crops compared to the control, likely due to extensive environmental losses of N during decomposition of cover crops before sweet potatoes were planted. Root nitrogen concentrations from the Austrian winter pea were observed to store leaf and root nitrogen at rates equivalent to the 25% recommended nitrogen fertilizer rate (20 kg N ha^{-1}). However, the cover crops cereal rye and crimson clover, stored sweet potato N equivalent to the control. Marketable yield showed statistically significant differences among the three cover crop

treatments and the nitrogen controls. The Austrian winter pea and the 60 kg N ha^{-1} plots produced greater yields than did the plots receiving the 80 and 120 N ha^{-1}. These findings indicate that higher rates of nitrogen application cause a steep decline in yields, potentially due to increased partitioning of biomass to aboveground biomass and away from root production.

The Influence of Winter Cover Crops and Nitrogen Fertilizer Rates on Nitrogen Uptake and Yield Response in Organic Sweet Potato (Ipomoea batatas) Production

by
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: The Influence of Winter Cover Crops and Nitrogen Fertilizer Rates on Nitrogen Uptake and Yield Response in Organic Sweet Potato (*Ipomoea batatas)* Production

Literature Review on Cover Crops

Nutrient management is a major component of agricultural production. Evidence of the use of organic amendments as a method for nutrient management dates back to as early 6,000 B.C. (Hergert et al., 2019). In recent years, scientific evidence has illustrated some of the extent at which organic amendments can aid in plant growth. One example of a widely used organic amendment in agriculture is the use of cover crops. Research on the use of cover crops has shown that cover cropping can provide benefits to erosion control, pest and disease management, carbon sequestration, soil water management and even other long term soil health benefits (Otto et al., 2020). Another major benefit and use in the case of cover crops is the incorporation of legume cover crops for their nitrogen fixation and subsequent release of nitrogen to the cash crop. Successful management of legume cover crops has the potential to reduce fertilizer inputs and is of particular importance to organic producers, where nitrogen inputs may be limited (Otto et al., 2020). However, some of these benefits may have not yet been well documented in sweet potatoes. This may be because the use of cover crops in sweet potato production has yet to be explored and tested to a similar extent as other crops where the benefits have been well documented, such as corn.

Living cover crops can provide benefits in erosion control, soil moisture, and pest and weed management (Jackson et al., 2008). Living cover crops are effective in nitrogen management for a cash crop by reducing leaching losses of nitrogen during some of the months that the cover crop is in production (Sedghi & Weil, 2022). Reduction in losses are accomplished by cover crops uptaking available nitrogen from the soil, and storing it in the biomass. Other nutrient benefits that cover crops provide are often seen after the cover crop is terminated. Decomposition of the terminated cover crop residues can become a source of nutrients in the soil for a cash crop to use. However, differences in nutrient composition of crop residues can dictate how the material is broken down, more specifically, the ratio of carbon to nitrogen in a plant residue. Carbon to nitrogen ratio (C: N) is a useful measurement for predicting how quickly nitrogen will be available in the soil for plant use. When the C: N ratio is above 25:1, immobilization occurs. Immobilization is the process of inorganic nitrogen converting into organic forms through microbial activity. This occurs when there is insufficient nitrogen in the decomposing materials required during the consumption of carbon as an energy source, requiring the microbes to access soil nitrogen stores. When the C: N ratio is below 25:1, mineralization occurs. Mineralization is the process where soil microbes release excess nitrogen into the soil solution through the decomposition of the organic material in an inorganic (plant available) form. Plants are unable to take up organic forms of nitrogen. Ammonium and nitrate are very limited in the soil, and are often a limiting factor for crop yield if no nitrogen is supplemented. From a plant growth perspective, immediate release of plant-available nitrogen that occurs during the mineralization process is valuable in crop management (Resham et al., 2021). Despite the wide use of cereal rye (*Secale cereale*) there is often concern of immobilization of N due to the high C: N ratios (Kaspar et al., 2007). The duration and magnitude of the immobilization is highly variable based on soil type, soil moisture conditions and termination method. This paper highlights the potential nutrient management benefits in using cover crops in sweet potato production. These cover crops included in this study are: crimson clover (*Trifolium incarnatum*), Austrian winter pea (*Pisum sativum*), and cereal rye (*Secale cereale*).

Crimson Clover is a commonly grown winter annual cover crop, specifically in North Carolina where sweet potatoes are also grown. A typical seeding rate used for crimson clover is 25-34 kg ha^{-1} broadcast six to eight weeks before the first frost. It is estimated that between 3920 to 6165 kg ha^{-1} of biomass can be produced (Crimson Clover, 2021). Crimson clover may be a good fit for incorporation in sweet potato production systems. Crimson clover grows well in sandy loam soils and can fix 8 to 188 kg N ha^{-1}, which aligns with current nutrient recommendations for sweet potatoes at 80 kg N ha^{-1} (Sustainable Agriculture and Research Education, 2012). However, there are mixed results on just how much nitrogen sweet potatoes require to produce maximum yields. Some evidence suggests that sweet potatoes may not benefit from any additional nitrogen if grown after crimson clover. In a study conducted by Monday et al. (2013), sweet potatoes were grown after a crimson clover cover crop with varying rates of pre plant ammonium nitrate (0, 50, 101 kg N ha^{-1}) applied to supplement nitrogen. It was found that there were no yield differences between any nitrogen treatments that were followed by crimson clover. The 101 kg N ha^{-1}

ammonium nitrate applied to the fallow no cover crop plot produced lower yields than all the crimson clover plots. Even the crimson clover with no added nitrogen produced higher yields than the conventional grown sweet potatoes with the 101 kg ha^{-1} ammonium nitrate treatment. While this study implies that the nitrogen supplied by the crimson clover exceeds the 101 kg N ha^{-1} applied to the fallow plot, this may not be the sole reason for the yield improvements. The nitrogen supplied by the crimson clover was not measured in this study by tissue analysis or soil sampling. There could be other advantages, such as weed control or pest control, to using crimson clover as a cover crop for sweet potato production that were not measured in this study. However, the effects of weed and pest control through crimson clover cover cropping are measured in other studies. For example, it was found that the use of crimson clover and oat (*Avena sativa*) mix as a mulch was comparable to the conventional tillage approach for weed and pest control (Jackson & Harrison, 2008).

Cereal rye is the most widely grown winter cover crop in the United States (Cover Crop Strategies, 2021). Cereal rye is often cited for benefits in erosion control, weed control, pest control, soil aggregate stability and its ability to scavenge residual nitrogen in the fall to prevent leaching (Rorick & Kladivko, 2017). Cereal rye is typically not used as a source of nitrogen due to the high C: N ratio. Late-stage cereal rye has C: N ratios in excess of 60:1. Whereas a legume, crimson clover maintains a lower C: N ratio if terminated in a timely manner and greater total nitrogen content than cereal rye at termination. Due to increased N availability the crimson clover decomposes more rapidly which is a microbially-mediated process and subsequently, provides a quicker release of plant available nitrogen for crop growth. Microbe species are influenced by cover crop chemical composition. Copiotroph microbes are present in nutrient abundant environments while oligotrophs are slow growing microbes often found present in nutrient restricted environments. Crimson clover residues contain greater total nitrogen leading to colonization of copiotrophs (Lundquist et al., 1999). Rye residues contain less total nitrogen which leads to a composition of oligotrophs (Lundquist et al., 1999). The water holding capacity of crimson clover is greater than cereal rye which can provide protection for microbial biomass and diversity during periods of water scarcity. Lundequist et al. (1999) highlighted the effects of the applications of two cover crop residues, cereal rye and crimson clover, on carbon and nitrogen dynamics in the soil, and consequential effects on microbial abundance, composition and growth.

Differences in the nutrient composition of a cover crop residue can influence both the water holding capacity, and the C:N ratio. In addition, mature cereal rye tends to have greater concentrations of lignin in the tissue. Lignin requires co-decomposition from bacteria and fungi often slowing the decomposition process and release of N, however this relationship is not always consistent (Sievers & Cook, 2018). Plant available nitrogen in the soil during specific growth periods is the fundamental parameter most relevant to crop yields. Nitrogen input costs for both conventional and organic growers are on the rise and constitute an increasingly large portion of field level expenses. The microbial mediated release of nitrogen from organic compounds such as cover crop residues may be a compelling source of nitrogen. This is only true if the growers know what the expected nitrogen replacement they can achieve and the practical challenges of incorporating cover crops into their rotation.

A study by Kuo et al. (1997) in North Carolina found that Austrian winter pea provides 85 kg N ha^{-1} when grown before silage corn (*Zea mays L.*) The C:N ratio of above ground biomass was 14:1. This same study found that cereal rye contributed 51.5 kg N ha^{-1} and had a C:N ratio of 33:1. The Austrian winter pea supplied a larger amount of N to the cash crop more rapidly due to more total N, and the lower C:N ratio of the above ground biomass. The characteristics of these cover crops found in this study may translate well into their use in sweet potato production. Because of the large amount of N supplied by the Austrian winter pea, and the low C:N ratio maintained, there may be potential for Austrian winter pea as a winter cover crop for sweet potato production.

Termination timing of a cover crop can play a large role in the C:N ratio of the residues. Dry matter accumulation for winter cover crops occurs rapidly prior to spring termination (Wagger, 1989). For example, a study conducted in the piedmont of North Carolina found that the C:N ratio of crimson clover varied from 13:1 to 15:1 within a two-week period from April 18 to May 1. The C:N ratio of cereal rye was found to be 36:1 and 44:1 respectively at the same sampling dates (Wagger, 1989). While the ratio and availability of nutrients is one factor that will influence the rate at which microbial growth can occur, other environmental factors such as moisture, can also be major influencing factors on growth and in turn the rate at which N mineralization can occur. Another major difference between residues that can potentially influence microbial populations is water holding capacity. Dry matter accumulation of a plant changes the ability of a residue to store water. Cereal rye residues maintain a lower water holding capacity than crimson clover residues. The lignin and insoluble carbohydrates in the rye are responsible for these lower water storage rates (Resham et al, 2021). It is well documented that available water can have a great influence in microbial biomass and composition of microbial communities (Schimel, 2018). After termination, the placement of the residue has a large impact on soil water dynamics. Residue left on the surface prevents evaporation and infiltration increasing water availability to the crop during the growing season (Acharya et al., 2019). Residue like cereal rye will have a longer impact on water dynamics as it is slower in breaking down.

During the growing season, the C:N ratio in the soil will decrease as a direct result of microbial growth. Microbe populations use the nitrogen from the cover crop residue for their own growth while releasing carbon in the form of CO_2 for respiration (Luo & Zhou, 2006). Microbe populations will increase exponentially when cover crop residues are introduced to the soil system. However, as the N nutrient sources from the residues become depleted, microbes will enter the stationary phase of growth. This begins to occur when the C:N ratio of the soil is about 25:1. As the death phase of the microbial growth curve begins, organic nitrogen is released as ammonium, a plant-available form of nitrogen (Luo & Zhou, 2006). Residues with high C:N will slow the growth curve of microbes as nitrogen release is at a sustained rate (Wagger, 1989). Residues with a less high C:N will lead to a rapid burst in microbial population and a faster decline in population. The growth is at a steeper rate, but the stationary phase of growth is sustained for a shorter duration of time, and death phases of growth are steeply pointed down. The growth characteristics can also vary depending on whether amendments are incorporated or left on top of the soil surface. For example, in a 1999 study, the incorporation of rye produced a rapid burst of microbial growth and activity (Lundquist, 1999). Incorporation of a crop residue for either cover crops will also lead to steeper microbial growth curves, as soil microbes have greater access to the nutrients sustained within the crop residues. Differences in nitrogen release from cover crops can influence soil microbial populations as nutritional needs of bacteria can vary between species (Lundquist, 1999). Different environmental conditions can result in differences in the diversity of microbes, and differences in which species may dominate a substrate (Resham et al, 2021). Crop residues that differ in carbon and nitrogen content will provide different environmental conditions that may encourage the growth of some microbial species over the growth of other microbial species. Thapa et al. (2021) found that crimson clover amended soils led to greater colonization of copiotrophs, microbes that have a competitive advantage when there are higher amounts of nutrients. Cereal rye amended soils led to greater colonization of oligotrophs, microbes that are slow growing and have the competitive advantage when resources are scarcer. Thapa et al. (2021) attributes these differences in microbe composition in the soil, to the differences in nitrogen content between cover crop residues. Crimson clover containing a larger amount of total nitrogen than the cereal rye allowed for these differences in microbe populations to occur (Thapa, 2021).

Abstract

This study evaluates three Fall-planted cover crop species for their effectiveness at managing nutrients for organic sweet potato production. The cover crops included were cereal rye (*Secale cereale*), crimson clover (*Trifolium incarnatum*), and Austrian winter pea (*Pisum sativum*). Over-winter fallow plots were also used to compare cover crop treatments with sodium nitrate applied at rates of 0, 20, 40, 60, 80, 120 kg ha^{-1}, representing 0%, 25%, 50%, 75%, 100%, and 150% recommended rates of nitrogen, allowing a fertilizer equivalency estimate. Cover crops were terminated and incorporated two weeks prior to sweet potato planting. The nitrogen availability in the soil, sweet potato (*Ipomoea batatas*) root yield, and tissue nutrient concentrations were measured throughout the growing season. The cover crops had a range of C: N with crimson clover commonly above 25:1, and even as high as 50:1, making rapid release of nitrogen through mineralization unlikely. However, the Austrian winter pea C: N consistently were lower than other cover crop treatments at 20:1. Tissue and root nitrogen concentrations from crimson clover and Austrian winter pea treatments were comparable to the 20 kg N ha^{-1} treatment. Sweet potato from the cereal rye treatment stored nitrogen at a lesser rate, equivalent to 0 kg N ha^{-1} control. However, the in-season soil data did not show apparent immobilization of soil nitrogen with the cereal rye. Marketable yield showed statistically significant differences among both the three cover crop treatments and the nitrogen controls. The Austrian winter pea and the 75% of the recommended nitrogen plots produced greater yields than the 100% and 150% treatments. These results show that the use of Austrian winter pea as a cover crop, is effective at contributing N to sweet potatoes. Findings also indicate that higher rates of nitrogen application cause a steep decline in yields, potentially due to increased partitioning of biomass to aboveground biomass and away from root production.

Introduction

Sweet potatoes are an important crop for North Carolina agriculture. North Carolina is the top producer of sweet potatoes contributing around 60% of the nation’s supply (USDA NASS, 2020). Organic production of sweet potatoes is a contributor to the state’s sweet potato production. Organic production is predicted to increase as consumers' preferences for organic continue to grow (Organic Industry Survey, 2022). Growing sweet potatoes organically is a challenging endeavor due to pest and weed control. Repeated cultivation is often required to prevent weed growth before the vines close between hills. In addition, providing adequate fertility to the crop has complications due to the restrictions in inorganic fertilizer use. In particular, in North Carolina, soil fertility with organic production is a problem as soils test generally high in phosphorus across the majority of the arable agricultural lands (Johnson et al., 2015). This is largely due to the intensive animal production in NC. The manure from animal production is spread across the soil statewide, but primarily in the Coastal Plains, where the majority of sweet potato acreage is located. Phosphorus is an immobile nutrient, meaning that it does not leave the soil environment with water movement or through mass flow. Growers who want to apply manure based on plant nitrogen needs are not always able to do so because phosphorus would be over applied.

This presents an even greater problem to organic growers who have a limited number of sources of nitrogen that can be used. One alternative to the use of manure and composts are winter cover crops. Cover crops can provide a viable source of nitrogen for a cash crop without contributing to P accumulation. Cover crop research has historically focused on corn or soy production. Research is limited on the challenges or benefits of using cover crops in sweet potato production and the potential N replacement value legumes provide. The goal of this study was to evaluate the integration of three common winter cover crops (cereal rye, crimson clover, Austrian winter pea), in North Carolina organic sweet potato systems.

Materials and Methods

Treatments and Experimental Design

This study was conducted at two locations across the span of two years for a total of four site years. Goldsboro, NC at the Cherry Research Station, and Kinston, NC at the Lower Coastal Research Station were selected as both locations are located in regions with intense sweet potato production and representative soils for their growth. This study consisted of nine treatments. Three of these treatments included cover crops: cereal rye, Austrian winter pea, and crimson clover. These cover crop treatments were not supplemented with any added nitrogen fertilizer. The other treatments included six varying rates of nitrogen fertilizer based on the percentage of recommended nitrogen rates for sweet potatoes set by the NCDA. These treatments included: 0%, 25%, 50%, 75%, 100%, 150%. The 100% recommended nitrogen rate is 80 kg ha^{-1}. This study was designed in a randomized block design which included five replicates (Figure 2). Each experimental unit was 8.5 m long and 9.1 m wide 28 feet long and included eight bedded rows for planting.

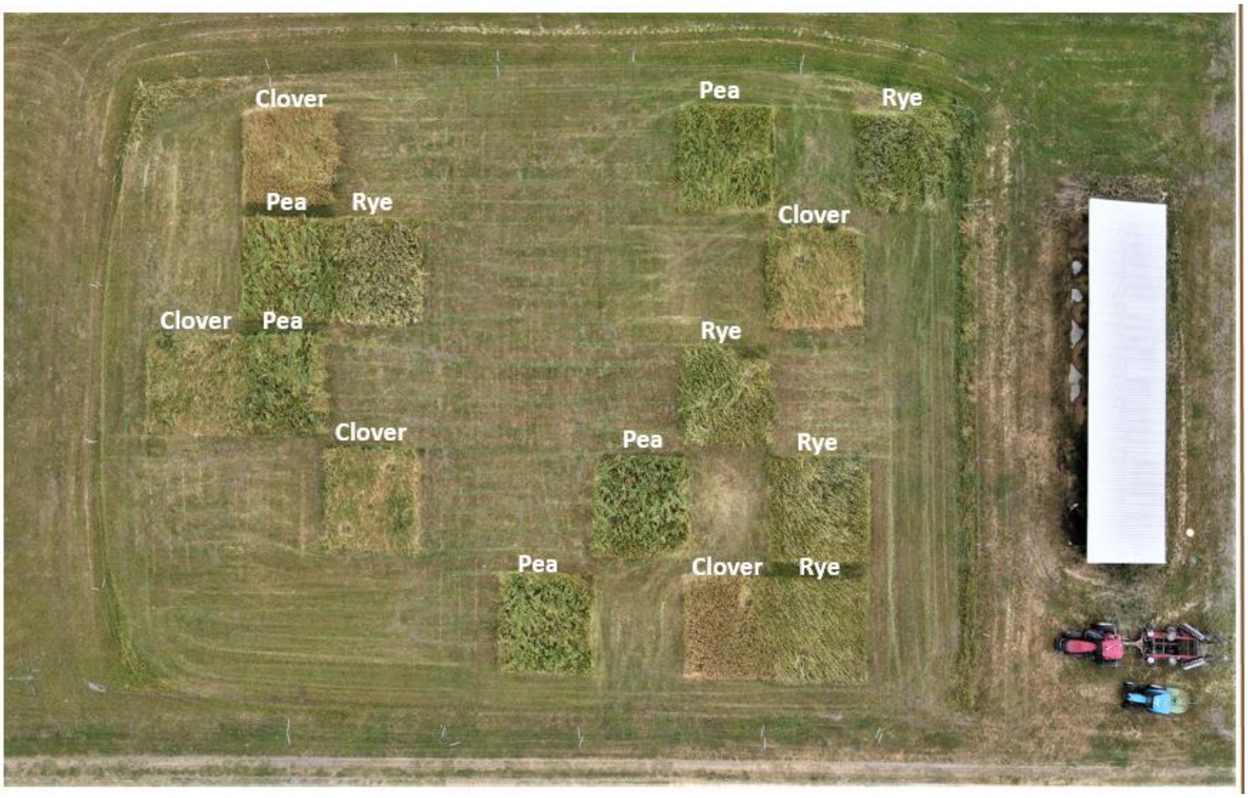


Figure 2.1: Cover crop blocks are laid out randomly across each of the five reps at Kinston research station in 2020.This photograph was taken the day of cover crop termination, two weeks before sweet potato planting

Field Management

The soil at the Goldsboro location was a Norfolk sandy loam (loamy, kaolinitic, thermic Arsenic Kandiudults). The soil at the Kinston location was a Goldsboro loamy sand (fine-loamy, siliceous, subactive, thermic, Aquic Paleudults). The previous crop grown at both locations was soy (*Glycine max*). Cover crops were broadcast seeded in October at rates of 38 kg ha^{-1} of cereal rye, 126 kg ha^{-1} of Austrian winter pea, and 38 kg ha^{-1} of crimson clover. The entire field was disced twice, terminating cover crops two weeks before an early June sweet potato transplanting (Table 1).

Fields were bedded prior to planting. Organic 'Covington' sweet potato slips were planted vertically 30.5 cm apart. It was observed that in plots where cereal rye was grown, sweet potatoes were not as well established due to rye residue being pressed down in the slot ("hairpinning") where the slip was being placed, preventing slot closure and soil contact. This may have been avoided by additional rounds of discing. Sweet potato slips were replanted by hand in the plots with poor establishment. Sweet potatoes were fertilized three weeks after slips were planted. Potassium fertilizer as muriate of potash was added in equal amounts to each treatment at the rate of 126 kg ha^{-1} K_2O to ensure that potassium deficiency would not be a limiting factor for plant growth. All other nutrients were at adequate levels, so no other fertilizers were applied. Sodium nitrate, known as "Allganic" from the distributer SQM was used as a nitrogen fertilizer source for the different fertilizer treatments. This nitrogen fertilizer was chosen because it is a certified organic fertilizer that is an inorganic and soluble form of nitrogen. This allows for a fertilizer replacement value of the cover crops to be calculated. Other certified organic sources of nitrogen such as manure may not release nitrogen for plant available use in as much of a consistent manner as would sodium nitrate confounding the exact nitrogen replacement values. We acknowledge that most growers do not often use sodium nitrate as their sole source of nitrogen, due to its cost and its historic use limitation in organic systems. The fertilizer for each treatment was divided by eight (one each row), to ensure that fertilizer would be distributed evenly across each plot. Both fertilizers were hand applied and incorporated through cultivation. Throughout the growing season, weeds were managed through weekly cultivation and hand weeding within rows. By July, the weeds were managed by only hand weeding because the sweet potatoes got large enough to grow in between rows. Deer and other large animal pests were managed by an electric fence that surrounded the field plot.

Table 2.1: Dates cover crop termination, sweet potato planting, fertilization, and harvest for each location in 2020 and 2021.

		Cover Crop Termination	Slip Planting	Fertilization	Harvest
Goldsboro	2020	May 7	June 5	June 29	Sept. 25
	2021	May 7	June 9	June 28	Sept. 17
Kinston	2020	May 11	June 4	June 26	Sept. 23
	2021	May 11	June 11	June 29	Sept. 22

Data Collection and Lab Analysis

Cover crop biomass was collected prior to termination. A 0.5 m^2 quadrat was used to measure an equal area randomly within each plot. Samples were collected by using pruning shears to cut material at ground level. The samples were dried and weighed for above ground biomass determination. Cover crop tissue was analyzed for carbon and nitrogen using an elemental analyzer (Perkin-Elmer 2400 CHN elemental analyzer; Perkin Elmer Corp, Waltham, MA, USA). Samples were analyzed by the Environmental and Agricultural Testing Services laboratory (EATS) at North Carolina State University. Sweet potato leaf tissue samples were collected every 30 days after planting until harvest and also analyzed for carbon and nitrogen using the same methodology as the cover crop tissue. Soil samples were collected every 30 days until harvest. This was accomplished by collecting 10 soil cores at a depth of 15 cm in-row across the middle six rows. Each of the ten soil cores collected per plot were homogenized and then frozen until analysis. Samples were analyzed for concentrations of soil NO3-N and NH4-N by a 1 M KCl extraction submitted to the EATS laboratory at NCSU for flow injection analysis methodology for colorimetric determination with a QuikChem IV (Lachat Instruments, Loveland, CO). Initial test levels for soil samples were taken June 10, 2020. No Initial soil samples were collected in 2021. The initial levels of total nitrogen in the soil are recorded in Table 2 to show differences in soil N before fertilizers were applied. Average soil N includes the sum of nitrogen in the form of ammonium and nitrogen in the form of nitrate. Harvest of sweet potatoes occurred in mid-September (Table 1) using a bed digger. Sweet potatoes were then collected by hand. At harvest, yield data was collected for each treatment. 6.096 meters were measured out in a representative area within each block. All sweet potato roots were collected within those 6.096 meters and graded based on USDA standards (Sweet Potatoes Grades and Standards, 2022). The jumbos (U.S. Extra No.1), U.S. No.1, U.S. No 2, and culls, sweet potatoes that were considered too small in diameter by US grading standards, were separated and weighed. Petites were considered as U.S. No 1 and separated accordingly. All grades were combined for a total root count and weight. Eight randomly selected No. 1 roots from each treatment were collected and a center piece 2.5 cm thick was diced and dried from each of the eight sweet potatoes. The sweet potato samples were dried at 65° C for 72 hours. Once dried, samples were ground to < 80-mesh. Carbon and nitrogen were once again analyzed using a Perkin-Elmer 2400 CHN elemental analyzer (Perkin Elmer Corp, Waltham, MA, USA) by the EATS laboratory at NCSU.

Growing Season Conditions

The growing conditions in winter 2019 and spring 2020 for cover crop growth were poor (Table 2). During the months of November 2019 through May 2020 26.95 inches of rainfall accumulated but the rain events did not appear to be distributed evenly enough to favor cover crop growth. In November 2020 through May 2021 34.20 inches of rainfall accumulated. This may have led to a much larger biomass for cover crops in 2021. As for sweet potato growth in 2021, the growing conditions were not as contrasting when looking at total rainfall crop received. However, the first two months of sweet potato growth, June and July, received 9.04 and 9.86 inches of rainfall respectively. In 2020, only 5.37 and 3.81 inches of rainfall was received in June and July. Early rainfall is highly conducive to sweet potato growth because the maximum number of storage roots a plant can provide are determined by water supplied in the early window after planting (Villordon et al., 2012).

Table 2.2: Precipitation from cover crop planting November 2019 to sweet potato harvest October 2021. Data was collected from the NCSU Climate Office.

Year	Month	Goldsboro Precipitation (in)	Kinston Precipitation (in)
2019	November	2.93	3.78
	December	3.30	2.34
2020	January	3.86	3.30
	February	4.44	6.94
	March	2.80	3.54
	April	4.40	4.77
	May	5.22	6.00
	June	5.37	4.91
	July	3.81	2.28
	August	5.67	10.34
	September	7.36	7.89
	October	2.14	4.06
	November	6.71	8.46
	December	5.33	7.42

Table 1.2 (continued).

2021	January	7.17	7.26
	February	7.55	8.08
	March	4.73	6.57
	April	.96	1.14
	May	1.75	1.76
	June	9.04	9.95
	July	9.86	7.74
	August	4.45	8.80
	September	2.40	1.61
	October	1.88	1.50

Statistical Analysis

All statistical analysis was conducted using SAS version 9.4 (SAS Institute, Cary, NC). An ANOVA was conducted using the PROC GLIMMIX procedure. For yield, yield grades and root nutrient concentration we considered treatment a fixed effect and replicate and environment (location x year) as random. Least squared means were determined if the treatment was significant ($P<0.05$), using a Tukey's HSD test. For the in-season tissue data sampled on day 30 and day 60 after fertilization at each site and year we used the repeated measure statement and again had treatment as the fixed effect and replicate and environment as random. Contrast statements were generated comparing legume cover crops and the control and legume cover crops and cereal rye.

For the yield, root nitrogen concentration, carbon concentration and C: N ratio of the roots a regression analysis was performed on the sodium nitrate rate treatments.

Results and Discussion

Cover Crop Biomass and C: N

In 2020, cover crops produced a low biomass (Table 3). Typical biomass expected for the Austrian winter pea and crimson clover are 3,000-5,000 kg ha^{-1}. In 2020 the biomass for crimson clover was 1,980 kg ha^{-1} in Kinston and 4,140 in Goldsboro kg ha^{-1} (Table 3). The Austrian winter pea was 1,900 kg ha^{-1} in Kinston and 1,350 kg/ha^{-1} in Goldsboro. An expected biomass for cereal rye is 8,000 kg ha^{-1}. In 2020 the biomass was 2,960 kg ha^{-1} in Kinston and 1,400 kg ha^{-1} in Goldsboro. These low biomasses are indicative of poor plant growth as a result of cover crops not receiving fertilization. In 2021, the total biomass for the cover crops were higher. Crimson clover produced 8,273 kg ha^{-1} in Goldsboro and 4,300 kg ha^{-1} in Kinston (Table 4). Austrian winter pea was consistently high at 5,778 and 5,262 kg ha^{-1} in Kinston and Goldsboro, respectively. Cereal rye also followed suit with higher biomass in 2021 with biomasses of 6,160 kg ha^{-1} in Kinston and 3157 kg ha^{-1} in Goldsboro.

Total nitrogen production in cover crops is a function of C: N ratios and total biomass. A greater biomass will typically result in a larger amount of nitrogen contained in the cover crop. In 2021, the total N produced by the cover crops is greater than in 2020 because of the larger biomass (Table 4). The recommended rate of nitrogen needed for sweet potatoes is 80 kg ha^{-1}. In 2021, the legumes were closer to that required rate. Crimson clover produced 37 and 76 kg ha^{-1} in Goldsboro and Kinston, respectively. Austrian winter pea produced 63 and 100 kg ha^{-1} in Goldsboro and Kinston.

A C: N ratio is a useful metric to understand the rate in which plant material will break down. When plant material is broken down, nutrients are released. When a C: N ratio is less than 25:1, N is released through mineralization. If a ratio is greater than 25:1, immobilization will occur. Immobilization ties up nitrogen resulting in a slower release for plant use. The timing and amount of nitrogen required by the sweet potato is not yet entirely understood. Some studies suggest that split application of nitrogen fertilizer is beneficial for sweet potatoes (Du et al., 2019). The release of N through cover crop degradation can act similarly to a split application of fertilizer. This is the case when the C: N ratio is higher and immobilization occurs. However, lower C: N ratios are typically desired when using cover crops as a source of nitrogen because some crops require N at larger amounts during critical windows in plant maturity. Currently in sweet potatoes, there is no such established window. The C: N ratio of the Austrian winter pea was 14:1 and 34:1 in Goldsboro and 21:1 and 24:1 in Kinston in 2020 and 2021 respectively (Table 3) (Table 4). These would typically be considered as favorable ratios because N would be rapidly released for sweet potato uptake. The C: N of crimson clover was much higher than the Austrian winter pea. This is due to termination timing of the cover crop. Samples for analysis were collected the day of termination which occurred in early May (Table 1). This is near maturity for the crimson clover. As crimson clover reaches maturity, the ratio of C: N increases as more dry matter is produced. Cereal rye had a C: N of 54:1 in Goldsboro and 80:1 in Kinston in 2020 (Table 3). In 2021, cereal rye maintained a C: N of 91:1 in Goldsboro and 87:1 in Kinston. These are high C: N ratio across both years and sites for nitrogen mineralization to occur. These ratios for cereal rye are consistent to what is expected for this cover crop.

Table 2.3: 2020 Cover Crop Biomass, Nitrogen Supplied, and C: N ratios.

Cover Crop	Goldsboro			Kinston		
	2020			2020		
	Biomass	N content	C:N	Biomass	N content	C:N
	kg ha $^{-1}$	kg N ha^{-1}		kg ha $^{-1}$	kg N ha^{-1}	
Cereal Rye	1400 b	19 b	54:1 a	2960 b	18 b	80:1 a
Crimson Clover	4140 a	82 a	22:1 b	1980 a	27 ab	31:1 b
A. Winter Pea	1350 b	40 b	14:1 b	1900 b	40 a	21:1 b

Table 2.4: 2021 Cover Crop Biomass, Nitrogen Supplied, and C: N ratios.

Cover Crop	Goldsboro			Kinston		
	2021			2021		
	Biomass	N content	C:N	Biomass	N content	C:N
	kg ha $^{-1}$	kg N ha^{-1}		kg ha $^{-1}$	kg N ha^{-1}	
Cereal Rye	3157 c	15 b	91:1 a	6160 b	31 c	87:1 a
Crimson Clover	4300 b	37 ab	50:1 b	8274 a	76 b	46:1 b
A. Winter Pea	5262 a	63 a	34:1 b	5779	100 a	24:1 b

Soil Nitrogen

The first soil samples were collected prior to fertilization at both sites in 2020 and 2021. There was no appreciable difference among treatments on initial nitrate because the values were low before fertilization occurred (Figure 3). This was consistent between sites and years with varying weather conditions. No appreciable nitrogen was measured in soils from cover crop treatments. This is consistent with findings by Hahn et al. (2021) who used legume cover crops in similar locations and soils for flue-cured tobacco (*Nicotiana tabacum*). This highlights the need for precision N management in the coastal plain region of the southeast.

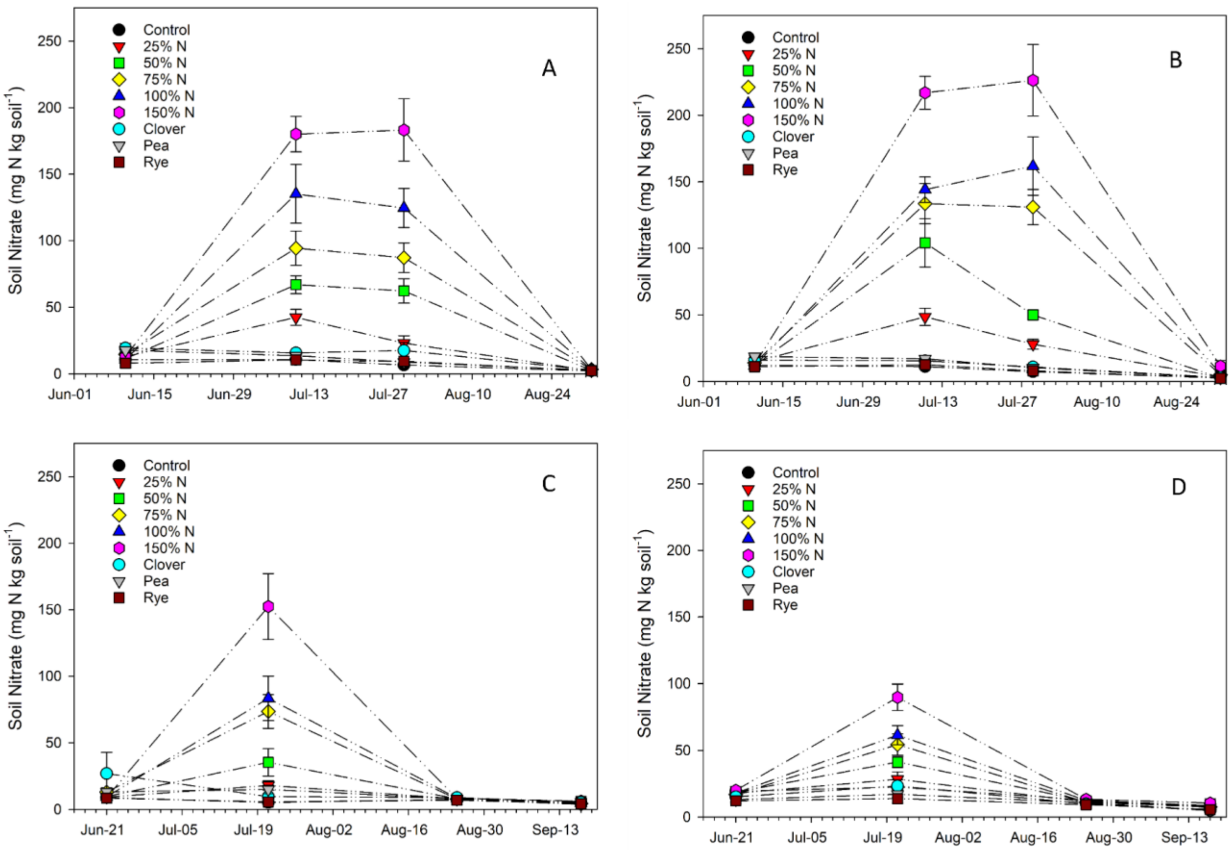


Figure 2.2: Soil nitrate concentrations over the growing season. a) Goldsboro 2020, b) Kinston 2020, c) Goldsboro 2021, d) Kinston 2020. Standard error (n=5)

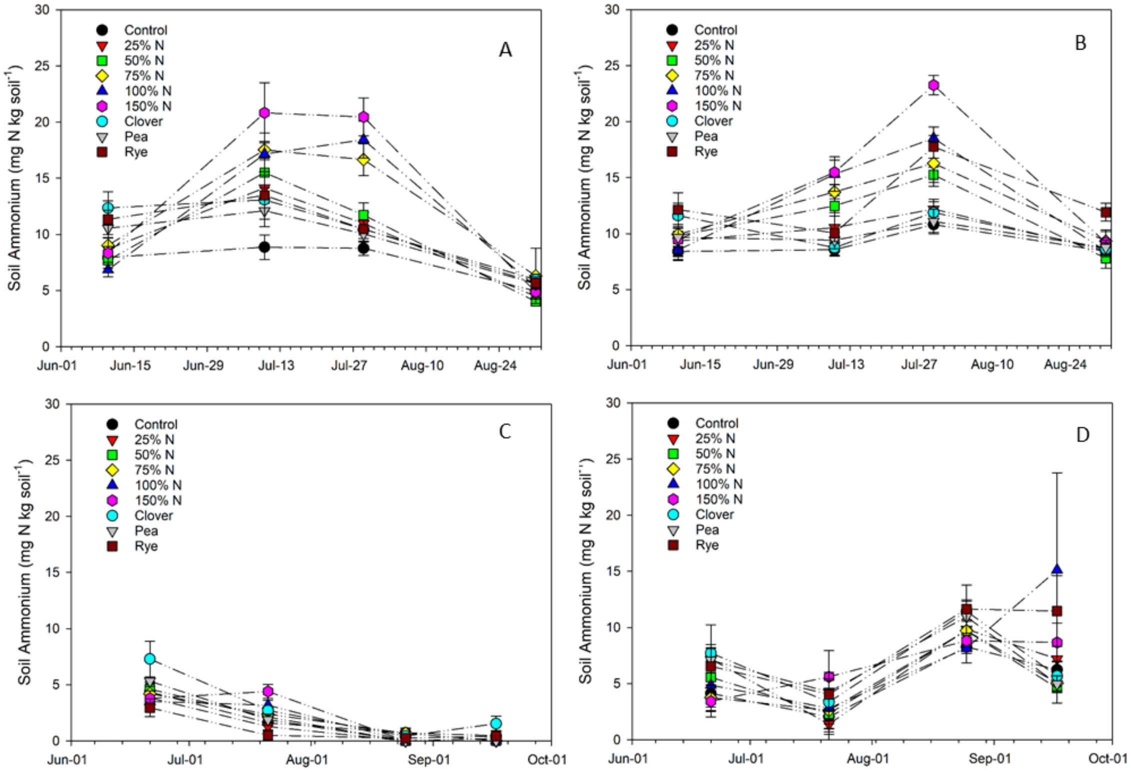


Figure 2.3: Soil Ammonium concentrations over the growing season. a) Goldsboro 2020, b) Kinston 2020, c) Goldsboro 2021, d) Kinston 2020. Standard error (n=5)

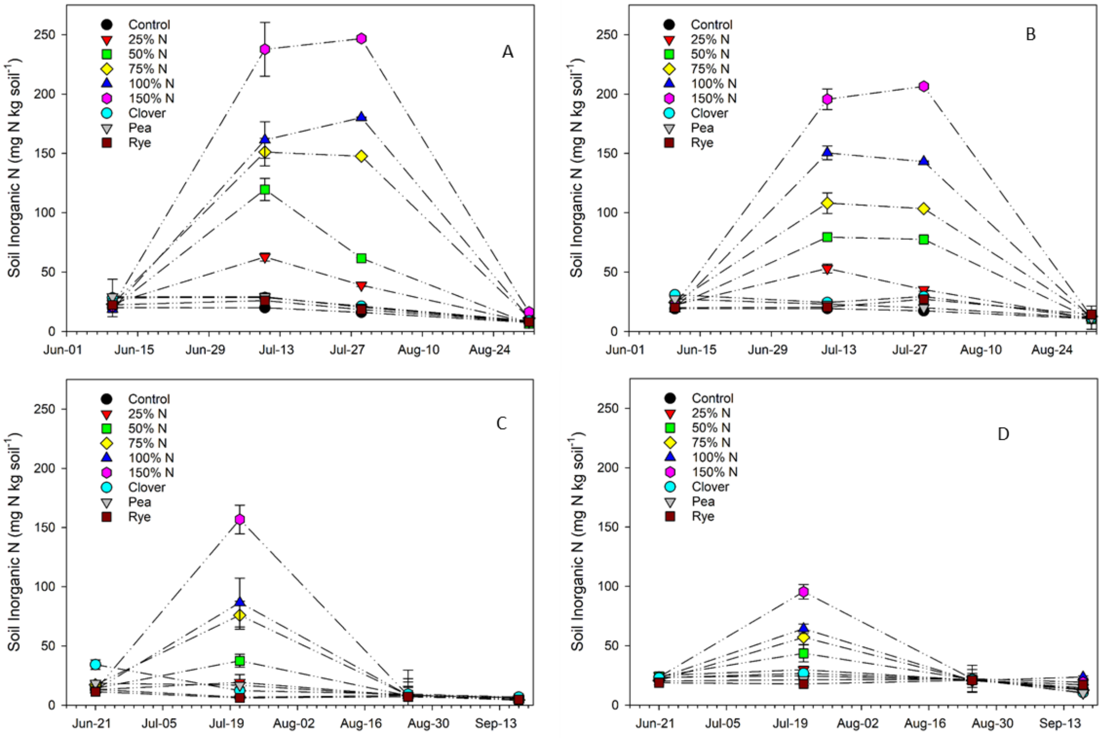
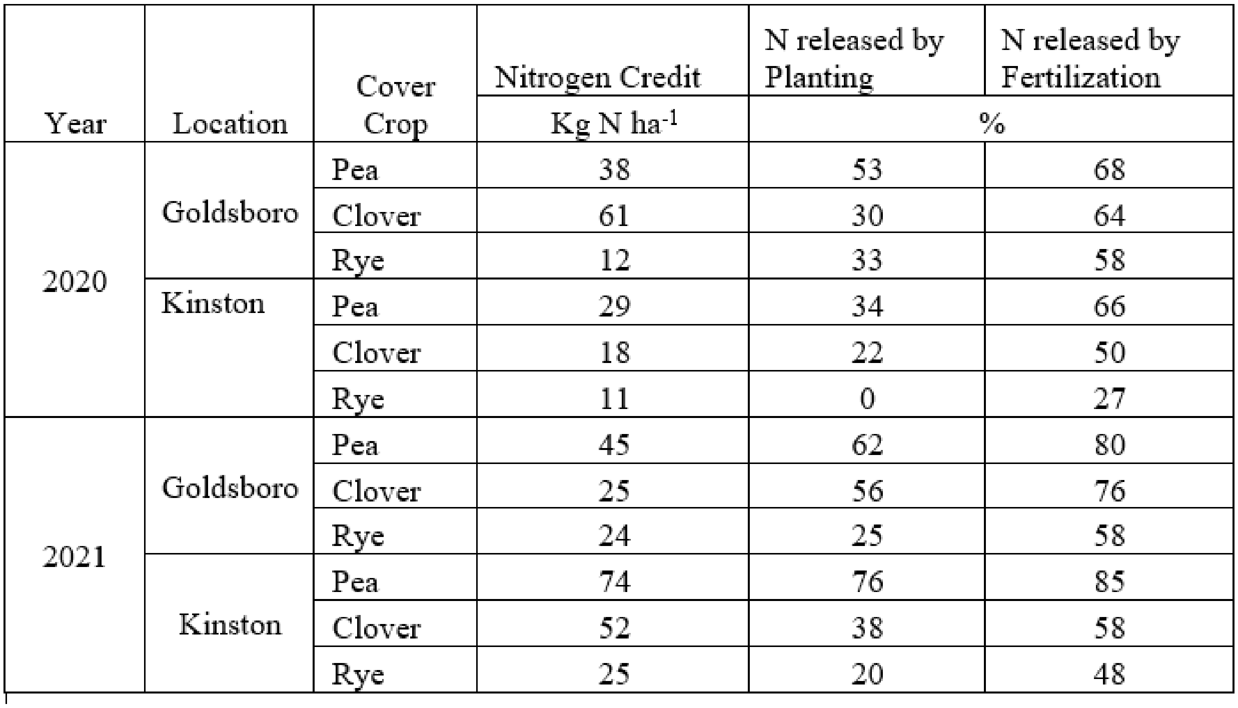


Figure 2.4: Soil Inorganic N concentrations over the growing season. a) Goldsboro 2020, b) Kinston 2020, c) Goldsboro 2021, d) Kinston 2020. Standard error (n=5)

N levels in the biomass of the legume cover crops indicated that there was comparable nitrogen to the 100% rate. For example, the Austrian winter pea in 2021 contained 63 and 100 kg N ha^{-1} (Table 4). However, no appreciable nitrogen was found in the soil samples from these treatments . In fact, the N levels in the soil of the Austrian winter pea were no different than the control in nitrate, ammonium, and total nitrogen. It is likely that much of the nitrogen present in the biomass of the cover crop was lost before the sweet potatoes were planted. Rapid decomposition, or decomposition of the quick fraction of plant material, begins to occur immediately after termination (Jahanzad et al., 2016). However, the timing of sweet potato planting may not coincide with the quick release of N in the early stages of decomposition. Investigation into the decomposition rates of the cover crops in this study was accomplished through the use of a cover crop nitrogen release calculator that incorporates weather conditions, cover crop properties and soil type called the CC-NCALC. This calculator utilizes cover crop information for each species, location, and year (NCALC, 2022). The product estimated replacement N available with each cover crop and the estimated N released by time of planting (Table 5). Based on the information inputs, the calculator showed that for the Austrian winter pea, 53% of N was lost between cover crop termination and sweet potato planting in Goldsboro 2020. For the same crop and location in 2021, an even greater amount of N was lost, 62%, before planting. There were losses even as high as 76% for the Austrian winter pea at the Kinston location in 2021 (Table 5). The other legume, crimson clover, had enough N contained in the biomass to support the 100% recommended rate, however the release rate ranged from 22-56% before planting (Table 3-5). The cereal rye had a much lower release rate due to the low Cgbb: N ratio (Table 3 and 4). The released N before sweet potato transplant can even be as low as 0% as seen in Kinston 2020. However, the total nitrogen supplied in that year and location was only 11 kg N ha^{-1}, which is well below the 100% recommended rate of 80 kg N ha^{-1}. While the Austrian winter pea contained an adequate amount of N in the biomass, the rapid phase of decomposition occurred within a shorter duration of time than the crimson clover or cereal rye. The soil samples in Figure 3-5, showed no differences in N between treatments on the first sampling date before fertilization. Rapid release of nitrogen post termination is a likely explanation for this occurrence.

Table 2.5: Estimated N credit available for each cover crop and the estimated nitrogen released by time of planting and time of first fertilization using the CC-NCALC calculator.



Year	Location	Cover Crop	Nitrogen Credit	N released by Planting	N released by Fertilization
			Kg N ha^{-1}	%	
2020	Goldsboro	Pea	38	53	68
		Clover	61	30	64
		Rye	12	33	58
	Kinston	Pea	29	34	66
		Clover	18	22	50
		Rye	11	0	27
2021	Goldsboro	Pea	45	62	80
		Clover	25	56	76
		Rye	24	25	58
	Kinston	Pea	74	76	85
		Clover	52	38	58
		Rye	25	20	48

Termination timing of a cover crop can play a large role in the amount of early nitrogen supplied in the soil. The window between cover crop termination and sweet potato planting is critical for nitrogen acquisition. Sites that have access to early irrigation may benefit from a later cover crop termination if nitrogen management is a priority to a grower. However, some studies suggest that a split application of nitrogen is preferable for sweet potatoes because too much early N is not beneficial to sweet potatoes (Smith & Villordon, 2009). Louisiana State University Extension recommends that nitrogen should be split or delayed 3-4 weeks after sweet potato planting because N uptake is greatest between 23-40 days after transplant (Smith & Villordon, 2009). Storage initiation occurs between 13-21 days after transplant, and nitrogen is not required for storage root designation (Smith & Villordon, 2009). Moisture is one of the primary initiating factors for storage root designation (Villordon et al., 2012). If the window between cover crop termination and sweet potato planting is reduced, and moisture is sacrificed for early nitrogen, this may cause more harm than good in terms of yields.

Leaf Nitrogen

Leaf N was the highest in the 75% N treatment. The control plot contained the lowest N concentration in leaves. The cover crop treatments were no different from one another, and were comparable to the control (Table 6).

Table 2.6: Leaf nitrogen and carbon tissue concentration averaged on days 30 and 60 after planting over the four site years (Goldsboro, Kinston, 2019-2020).

Treatment	Rate	N Concentration	C Concentration	C:N
	$kg\ N\ ha^{-1}$	(%)	(%)	
Cereal Rye	0	3.39 cd	39.9 a	12.0 ab
Crimson Clover	0	3.46 bcd	39.7 a	11.7 abc
Austrian Winter Pea	0	3.45 bcd	39.7 a	11.7 abc
Control (0%)	0	3.25 d	39.1 ab	12.4 a
25%	20	3.53abcd	39.5 ab	11.4abc
50%	40	3.7 abc	39.5 ab	10.9 bc
75%	60	3.82 a	39.5 ab	10.6 c
100%	80	3.8 ab	39.3 ab	10.6 c
150%	120	3.6 abc	38.8 b	10.9 bc
Statistics		**Pr>F**		
Treatment		<0.0001	0.0021	<0.0001
Sampling Date			<0.0001	<0.0001
Treatment x Date			0.4259	0.2687
Contrasts				
Legume vs control		0.0295	0.0070	

The 30 and 60 day average of the N concentration and C concentration varied between treatments. The 75% nitrogen contained a higher N% in the leaves than any of the cover crop treatments or control (Table 6). On the other hand, the C% in leaf tissue was greater in the cover crop treatments than the 150% plot. The only differences in C: N ratio were that the cereal rye and control had significantly higher ratios than the 75% and 100% rates. The carbon and nitrogen dynamics within the leaf tissue did change at the 90 day sampling. The C: N ratios were much higher regardless of treatment. For example, the C: N of the control in the 30 and 60 day samples was 12.4:1 (Table 6), while the C: N of the control in the 90 day sample is 15.8:1 (Table 7). Another difference between carbon and nitrogen dynamics between the two sampling dates is that there was no significant difference between any of the treatments. This implies that treatments may influence early leaf nitrogen, does not have lasting effects on leaf N by late in the growing season.

Table 2.7: Nitrogen and carbon tissue concentration and C: N on day 90 after in 2021.

Treatment	Rate (kg N ha^{-1})	N Concentration (%)	C Concentration (%)	C:N
Cereal Rye	0	2.46	40.9	16.8
Crimson Clover	0	2.57	40.4	16.0
Austrian Winter Pea	0	2.61	40.7	15.9
Control (0%)	0	3.17	40.6	15.8
25%	20	2.81	41.0	15.2
50%	40	2.69	41.2	15.9
75%	60	2.64	40.3	15.7
100%	80	2.65	40.0	15.6
150%	120	2.90	40.7	14.5
Statistics		**Pr>F**		
Treatment		n.s.	n.s.	n.s
Contrasts				
Legume vs control		n.s.	n.s.	n.s.
Legume vs Rye		n.s.	n.s	n.s.

*analyzed separately from as samples were only taken in 2021 for the late September sampling, location considered random

Figure 2.5: Drone image of sweet potato plot taken mid growing season. Visual differences in leaf color between treatments can be seen.

Visual differences among treatments could be seen by mid growing season (Figure 6). Leaf color is often influenced by nitrogen uptake. The higher application rates of nitrogen appeared to have "greener" colors visually compared to the rye cover crop and lower nitrogen application rates.

Nitrogen in Harvested Roots

Differences among treatments in root N at harvest were observed. Sweet potatoes grown in the cereal rye plots contained the lowest amount of nitrogen in the root tissue at 0.78% (Table 8). The highest rates, specifically the 150% rate, contained the highest amount of nitrogen in the tissue at 1.22% (Table 8).

Table 2.8: Sweet potato root nitrogen concentration at harvest and N uptake by the roots over the four site years (Goldsboro, Kinston, 2019-2020).

Treatment	Rate	N	N Uptake	C	C:N
	(kg N ha^{-1})	(%)	kg N ha^{-1}	(%)	
Cereal Rye					
Crimson Clover	0	0.78 e	170 b	39.3 ab	51.6 a
Austrian Winter	0	0.90 cde	207 ab	39.8 a	46.7 ab
Pea.	0	0.95 bcd	235 ab	39.7 a	42.5 bc
Control (0%)	0	0.88 de	205 ab	39.7 a	48.9 ab
25%	20	0.93 cde	208 ab	38.9 b	43.0 bc
50%	40	1.04 bc	239 a	38.9 b	38.3 cd
75%	60	1.08 ab	271 a	38.8 b	36.5 cd
100%	80	1.10 ab	206 ab	38.7 b	36.4 cd
150%	120	1.22 a	227 ab	39.0 ab	33.6 d
Statistics		**Pr>F**			
Treatment		<0.0001	0.0014	<0.0001	<0.0001
Contrasts					
Legume vs control		n.s.	n.s.	n.s.	0.0271
Legume vs Rye		0.0006	0.0079	0.0202	0.0003

What was described in Table 5 was also confirmed in the regression analysis where a linear regression was found to be significant with increasing N concentrations with increasing N application rates (Figure 7). The point at which N rate does not increase plant N uptake is greater than what has been tested in this study.

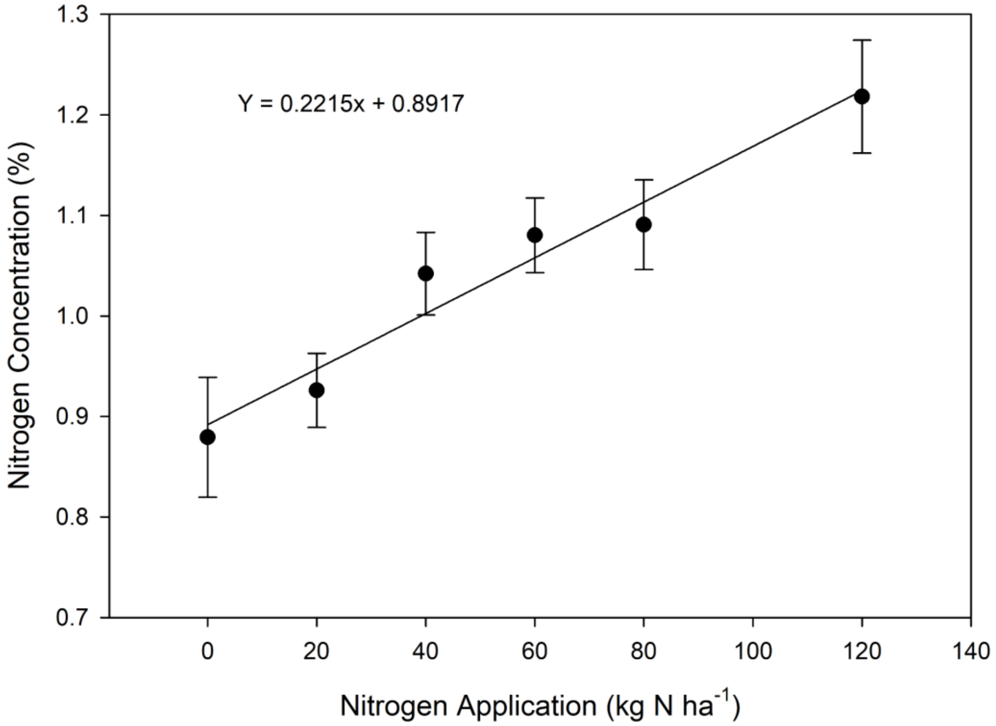


Figure 2.6: Linear regression of nitrogen concentration in the sweet potato roots with increasing rates of nitrogen application over the 4 site years.

A study conducted by Phillips et al. (2005) compared the yields produced by different nitrogen fertilization rates in sweet potatoes to determine the optimum nitrogen rate. The results of this study showed that although rates higher than 28 kg N ha^{-1} did not improve sweet potato yields, sweet potato N uptake increased up to a rate of 84 N ha^{-1}. In this study we are seeing a plant uptake response increase even at the highest application rate of 120 kg N ha^{-1} (Figure 7). While a similar trend in plant response is seen in this study as Phillips et al. (2005), plant uptake increased at higher rates. This could be possibly due to the different cultivars used. This study was conducted on the Covington cultivar while Phillips et al (2005) used the Beauregard cultivar which is known to require less nitrogen (Yencho, 2008).

Monday et al. (2013) compared the use of crimson clover as a winter cover crop with varying supplemental rates of nitrogen in sweet potato production to a conventional system of 101 kg ha^{-1} ammonium nitrate. Their study did not find any significant differences in yields between sweet potatoes grown after crimson clover with no added nitrogen to the crimson clover with supplemented nitrogen at any of the rates tested (50 and 101) kg N ha^{-1}. When compared to the conventional system, the ammonium nitrate at 101 kg N ha^{-1} produced sharply lower yields than any of the crimson clover treatments. Based on their study alone, it would appear that crimson clover is supplying a great extent of nitrogen if all crimson clover treatments outperformed the non-cover crop treatments. It is also implied in those results that the crimson clover cover crop supplied more nitrogen to the sweet potatoes than the conventional of 101 kg N ha^{-1} ammonium nitrate. But this explanation may not be the case. It is seen in Table 6-8 that sweet potatoes grown after cover crop treatments store less nitrogen than the 100% rate. Further, soil data showed that soil in the cover crop plots did not contain any additional nitrate than the control. It is possible that Monday et al. (2013) saw increased yields in cover crop plots for a reason other than increased nitrogen availability in the soil or increased concentration of nitrogen stored. The fertilizer equivalency estimate for cover crops has variation between studies. While Monday et al (2013) found that crimson clover can out supply 101 kg/ha of N, Fernandes et al. (2018) found that legume cover crops *Crotalaria spectabilis* and *Mucuna aterrima* provided the equivalent of 35.2% of required, or recommended to be required, N for sweet potatoes.

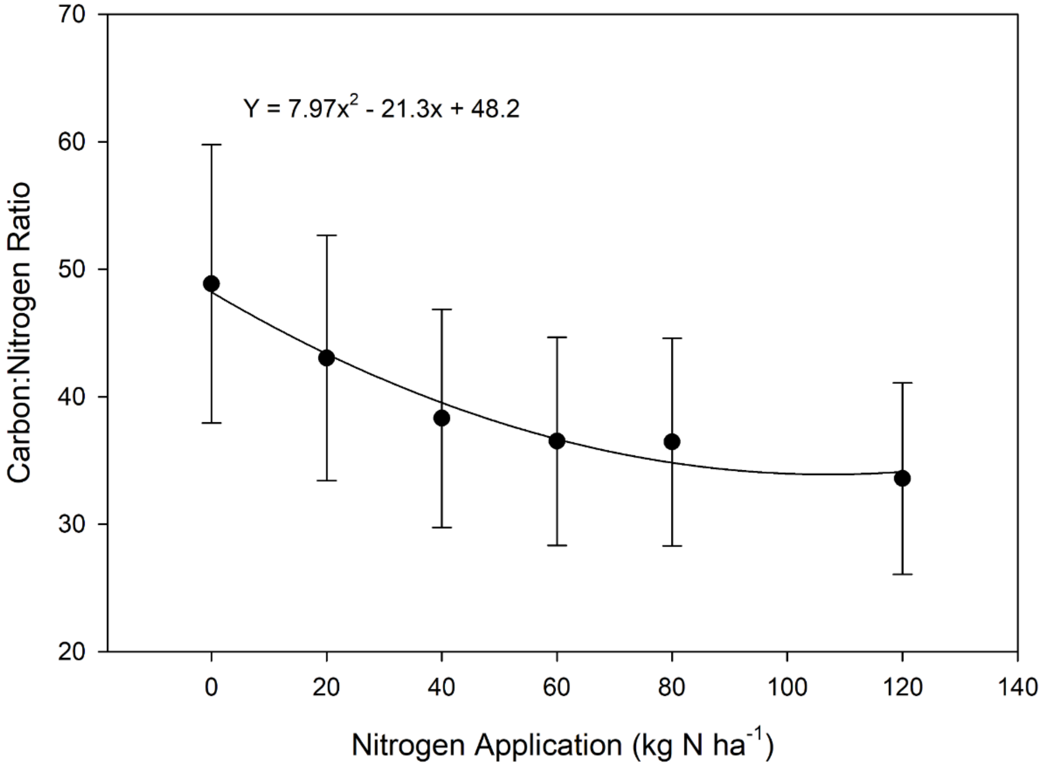


Figure 2.7: Quadratic response regression of increasing rates with nitrogen application over the 4 site years for C: N ratio of the sweet potato roots.

The ratio of C: N of the sweet potato roots was influenced by treatment. There was a quadratic response of C: N decreasing as nitrogen rate increased (Figure 8). The ratio of C: N in crops can have nutritional implications such as protein content. A study conducted by Purcell et al. (1982) investigated differences in protein content in sweet potatoes grown in soil with varying nitrogen fertilization rates. This study found that although sweet potatoes will continue to take up and store N when N is more available. This is a similar trend to what is seen in Figure 8. But this study also found that although root nitrogen storage increased with higher rates, the protein content did not increase. However, Phillip et al. (2005) found that crude protein increased up to the 75% recommended N rate. Further investigation into the nutritional differences between N concentrations in sweet potatoes may be useful to fully understand the relevance of excess N uptake in sweet potatoes.

Differences in Yields

Despite the increased nitrogen accumulation in the plant tissue with higher rates, yields were not improved. In fact, the two highest rates of nitrogen, 100% and 150%, were statistically lower than the 75% recommended rate and the Austrian winter pea. The 150% rate only produced 18.7 t ha while the Austrian winter pea produced 25.1 t ha (Table 9). A linear platea is often seen when evaluating the efficacy of nutrient rates for a crop. However, in this study, higher rates led to a drop in yields. The cereal rye and crimson clover cover crops were no different than the control of no added nitrogen (Table 9).

Table 2.9: Average marketable yields by treatment and total root biomass over the four site years (Goldsboro, Kinston, 2019-2020).

Treatment	Rate (kg N ha^{-1})	Marketable Yield Means (t/ha^{1})	Total Root Biomass
Cereal Rye	0	22.5 ab	22.8 ab
Crimson Clover	0	23.8 ab	22.6 ab
Austrian Winter Pea	0	25.1 a	25.4 a
Control (0%)	0	24.1 ab	24.4 ab
25%	20	22.9 ab	23.2 ab
50%	40	23.5 ab	23.6 ab
75%	60	25.7 a	26.2 a
100%	80	18.7 b	19.1 b
150%	120	18.5 b	18.8 b
Statistics		**Pr>F**	
Treatment		0.0003	0.0012
Contrasts			
Legume vs control		n.s.	n.s.
Legume vs Rye		n.s.	n.s

There were also no differences between the control 0% and the 25%, and 50% treatments. This implies that perhaps no additional nitrogen is needed to improve yields. However, the 75% nitrogen did improve yields more than the 100% and 150%. Sweet potatoes stored additional nitrogen when more nitrogen was available at a linear rate (Figure 7). But the sweet potato yield response did not follow suit. One explanation for the decline in yields at higher rates is the occurrence of salt injury. Because sodium nitrate was the fertilizer source that was used, the sodium could have caused injury to plant growth. However, salt injury at the higher rates is unlikely to have occurred because there was no evidence of salt injury in the higher rate plots. In fact, visually the high application plots were greener with no apparent stand loss (Figure 3).

Another explanation for the decline in yields is that the yields were all around poor, thus not needing nitrogen at the 100% recommended rates. However, in the case of this study, yields were above average in all treatments except the 100% and 150% rates. In North Carolina the average sweet potato yield is 19.6 t/ha^1 (USDA NASS, 2021). The yields seen in this study are comparable, if not above average, to yields in a conventional system. Thus, low yields is not a likely explanation for the yield response at the higher rates seen in this study.

The last and most likely explanation is that the sweet potato plant is putting less energy in root storage and instead using energy on above ground biomass production. In the sweet potato crop, there appears to be a specific nitrogen threshold at which the sweet potato decreases allocation of photoassimilates to the root (Bush, 2020; Okpara et al., 2009). A study on nitrogen rates in Nigeria for sweet potatoes found that the optimum rate of nitrogen was 80 kg N ha^1 when the initial soil test level is below 1% and 40 kg N ha ^{1} when the initial soil N is lower. However it is important to note that this study did not test any rates between 40 and 80 kg N ha^1 (Okpara et al., 2009). Our study found decline in yields at rates higher than indicated above, which we attributes to the excess nitrogen encouraging luxuriant vine growth at the expense of storage root bulking. Further, the older and shaded leaves in the lower parts of the crop canopy reached their light compensation point and may have become sinks rather than sources of assimilate (Okpara et al., 2009). The absolute threshold appears to be between the 75% and 100% rate in the case of Okpara et al (2009), and in the case of this study also. This could explain why there was a sharp decline in yields, 25.7 t/ha^1 at the 75% rate to 18.7 t/ha^1 at the 100% rate (Table 5), when the marginal increase in N added between the 75% and 100% was not necessarily a great amount. Over a 27% decrease in marketable yields is seen between these two rates. A difference to such an extent is not seen between the 100% and 150% despite the marginal increase in N being double that of the marginal increase between the 75% and 100%. This could suggest that the partitioning to above ground biomass plateaus beyond a certain nitrogen application rate is in excess of what the crop requires.

While many sweet potato studies also observed a decline in yields at their highest rates of nitrogen tested, few studies draw the same conclusion as to what amount of added nitrogen yield decline begins to occur (Purcell et al., 1982; Phillips et al., 2005; Schultheis et al., 1999; Yencho et al., 2008). This may be because the interaction between sweet potatoes and environmental factors dramatically influences their nutrient requirements. Rain is one example of a major factor that influences the optimal N rate for sweet potatoes. Because sweet potatoes are grown in sandy soil, larger precipitation events early after N application can greatly influence the total amount of N that will be supplied to the plant. If at a high rate of N triggers a plant response to switch into vegetative growth instead of root storage, and the amount of N that is supplied to a sweet potato is heavily influenced by rain, it may be best to make conservative recommendations because over-applying may be detrimental to yields. Further, the amount of rain is an unknown variable. Initial rain influences the number of roots designated to storage, number of roots influences yields and fertilizer required (Villordon et al., 2012). Rain can leach applied nitrate. This makes consensus on nutrient recommendations difficult because the specific amount of nitrogen necessary for maximum yields will be difficult to replicate when rain influences both nitrogen availability and the designated number of sweet potatoes grown. While in some crops, additional nutrients supplied may not improve yields, excess nutrients can increase plant uptake and improve the nutritional quality of a crop. In the case of sweet potatoes, there is a linear response in nitrogen storage and nitrogen rates. However, additional nitrogen storage may not even improve the nutritional quality of the sweet potato. In North Carolina, Purcell et al. (1982) found that although sweet potatoes will continue to take up and store N when N is more available, yields will not increase at any rate. But this study also found that although root nitrogen storage increased with higher rates, the protein content did not increase. This implies that not only will excess nitrogen not improve yields, but it will not improve nutritional quality either. The distribution of grades, within the yield of each treatment, did not vary among treatments. The average marketable yield, that was used to evaluate treatments above, includes the total weight of jumbo, US ones, and canners combined. There were no significant differences among treatments in total weight for US ones, grade two, jumbo, and even culls (Table 8 and 9). This implies that cover crop treatments or varying rates of nitrogen does not influence distribution of grades.

Table 2.10: Percent Grade of Total Sum.

Treatment	Rate	Jumbo	Grade Ones	Grade Two (Canner)	Culls
	(kg N ha^{-1})	Percent %			
Cereal Rye	0	15.33 a	47.85 a	36.83 a	1.58 a
Crimson Clover	0	16.02 a	49.86 a	33.88 a	1.33 a
Austrian Winter Pea	0	13.19 a	47.67 a	39.14 a	1.39 a
Control (0%)	0	10.47 a	53.43 a	36.10 a	1.09 a
25%	20	10.48 a	51.08 a	38.43 a	1.41 a
50%	40	9.89 a	46.11 a	37.27 a	1.77 a
75%	60	14.64 a	46.11 a	39.25 a	1.77 a
100%	80	10.08 a	50.65 a	39.30 a	1.82 a
150%	120	18.23 a	48.31 a	33.46 a	1.86 a
Statistics			**Pr>F**		
Treatment			<0.05		

Table 2.11: Mean Yield for each Grade by Treatment.

Treatment	Rate (kg N ha^{-1})	Jumbo (t/ha^{1})	Grade Ones Means	Grade Two (Canner) Means	Culls
Cereal Rye	0	3.821 a	9.398 a	9.127 a	3.821 a
Crimson Clover	0	3.775 a	10.452 a	9.327 a	3.775 a
Austrian Winter Pea	0	3.407 a	10.939 a	10.546 a	3.407 a
Control (0%) 25% 50% 75% 100% 150%	0	2.692 a	12.202 a	9.117 a	0.441 a
	20	2.637 a	11.308 a	8.874 a	2.637 a
	40	2.644 a	11.782 a	8.897 a	2.644 a
	60	4.314 a	10.671 a	10.605 a	4.314 a
	80	2.178 a	9.425 a	7.093 a	2.178 a
	120	3.550 a	8.529 a	6.387 a	3.550 a

Fertilizer recommendations for sweet potatoes vary widely, specifically, nitrogen recommendations. Some studies suggest that no nitrogen should be added, such as the case in a study conducted by Purcell et al. (1982). Purcell et al. showed that the highest yields were when N was at 0 compared to the other treatments of 56 kg ha^{-1} and 112 kg ha^{-1}. Phillips et al. (2005) found that sweet potato yield did not improve at rates higher than 28 kg ha^{-1}. Other studies suggest that 56 kg/ha is optimal (Schultheis et al., 1999). And other studies even suggest that 100.9 kg/ha will produce higher yields (Yencho et al., 2008). This variation in sweet potato response to nitrogen could be due to differences in soil texture, weather conditions, planting and tillage history, weed management, and sweet potato variety grown. Phillips et al. (2005) attributes the variation in response to nitrogen rates to be due to precipitation. But other crops such as maize seem to have more consistency in response to nitrogen fertilizer despite being subject to those same external variables. Investigation into how environmental factors influence nutrient behavior in sweet potato production may be necessary in order to specify the best fertilizer application rates. Tsuno & Fujise

(1964) investigated such influencing factors. Their study found that the dry matter produced in sweet potatoes is governed by potassium uptake. But soil temperature governs nutrient acquisition and subsequently dry matter production (Tsuno & Fujise 1964). Above ground biomass and leaf area was dictated by nitrogen uptake. Their study shows that there are major interactions between the soil temperature and precipitation, and potassium and nitrogen requirements.

The timing of N supplied to the sweet potato was not a variable in this study. However, other studies show that the timing of N application is significant for plant response. Phillips et al. (2005) found that nitrogen application for sweet potatoes is best two to three weeks after transplant. The use of cover crops as a source of nitrogen makes the timing of N supplied more difficult to control. This is because when cover crops are terminated, the timing of the N supplied to sweet potato will vary. This could be a potential downside to the use of cover crops until further research is conducted on how to more effectively synchronize cover crop nitrogen mineralization with crop nitrogen demands. Typically, two weeks are required for cover crops to decompose between termination and sweet potato planting. The N released by the cover crops will begin shortly after termination if the C: N ratio is low. The N released by the cover crops may extend over a period of time if the C: N is higher. Future research may benefit in comparing different termination timing of cover crops and different C: N ratios to better understand how these variables influence sweet potato nitrogen use.

Conclusion

The majority of available research on legume cover crops is emphasized for the benefits that cover crops can provide in corn production. These benefits have not yet been established to the same extent in sweet potato production. Research that is tailored for sweet potatoes may incorporate cover crops that align with a June sweet potato planting. The results in this study indicate that the use of legume cover crops: Austrian winter pea and crimson clover, contain a modest supply of nitrogen in the biomass, however, much of that N to rapid release before the sweet potatoes are transplanted. This study also indicated that cereal rye is not an effective cover crop to utilize in sweet potato production due to added labor required to properly terminate this cover crop to bed rows. The soil data indicated very little nitrogen released during the growth period of the sweet potato. Using a nitrogen release calculator, it appeared that large portions of the cover crop nitrogen is released before planting occurs and certainly before significant N uptake happens. The traditional termination of a cover crop one to two weeks before planting to allow for water recharge normally recommended does not work at this time of the year. In late May and early June conditions are hot and wet, causing rapid decomposition of this material. A natural continuation of this research is evaluating the termination and planting of sweet potato at the same time to improve nitrogen synchrony with the N release and ideally allow these legumes to provide a more meaningful amount of N to the sweet potatoes. This study showed that high applications of N consistently reduced sweet potato yields. Unlike crops like corn that will plateau in yield response with excessive N application, sweet potatoes have an important N threshold that needs to be well documented if more complex N programs are going to be used including the use of cover crops and alternative organic amendments. Currently, there is no consensus on the optimal rate of any nutrient, specifically nitrogen, in sweet potato production. In order to optimize cover crop use, nutrient dynamics in sweet potatoes should be better understood. Sweet potatoes are a valuable crop to North Carolina agriculture, and an important source of calories in other parts of the world. However, with increasing input costs, there needs to be a concerted effort to harmonize and establish fertility recommendations that are consistent and avoid yield declines with cover application.

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Chapter 2: Polyhalite as an alternative potassium fertilizer for sweet potato (*Ipomoea batatas*) production in North Carolina

Abstract

This study evaluated the use of polyhalite as a source of potassium fertilizer for sweet potato compared to the more commonly used Muriate of Potash (MOP). The rates for MOP and polyhalite were 32, 63, 126, and 189 kg K_2O. Controls included a plot with no added fertilizers, a control for nitrogen, and a control for nitrogen and sulfur. Lastly, a MOP and micronutrients treatment was included to examine the impact of the micronutrients within Polyhalite. Yields, yield quality, and nutrient uptake of sweet potato and soil nutrient status were evaluated. The evaluations were conducted in 2019 and 2020 at the Lower Coastal Plain Research Station in Kinston N.C. and the Cherry Research Station at Goldsboro N.C. When analyzed as individual treatments, there were no observed differences in the marketable yield among treatments. However, a regression analysis found a statistically significant quadratic response to fertilizer application regardless of source (MOP vs Poly). With a peak marketable yield of 37 t ha-1 at ~100 kg K_2O ha^{-1}, before declining in the two highest rates of application. Sulfur tissue and root concentrations were responsive to polyhalite application, with the highest rate having a 15% increase in sulfur compared to the control. Whereas results showed that there were no differences among any treatments in nutrient uptake for K, Ca, and Mg. The distributions of grades among treatments did vary, in that some of the polyhalite treatments produced a higher proportion by total weight of jumbos and a smaller proportion of canners when compared to the no fertilizer control. Soil samples showed that MOP initially released a higher amount of potassium than polyhalite. However the amount of potassium sustained in the soil by the end of the season was equal between treatments when initial K levels were low. These findings suggest that polyhalite can be a useful source of potassium and its use will result in comparable responses to the MOP.

Introduction

Diversification provides advantages to the food system (Manning, 2015). Over exposure of a single input makes the food system vulnerable to shortages that may arise, such as when unexpected shortages of key inputs occur (e.g., Mango et al., 2018). Repeated use of the same herbicide will produce weed resistance (Blythe, 2021). The use of a variety of chemicals to control weed and pest issues is critical to agricultural practices (Holt et al., 2013). While a range in type of herbicides and pesticides is one example of how diversification of an agricultural input mitigates risk, fertilizer sources are another example of a critical input that requires diversification for food security. Diversification in fertilizer inputs reduces risk as producers have options when there are low reserves or disruptions in supply (Manning, 2015).

A critical motivation for exploring fertilizer source diversity arises from how fertilizer sources are distributed. Seven countries produce 90% of the world's potash supply, of this supply, 36% is sourced from Canada and 12% from Russia (Production and Use of Potassium, 1998). With such a large percentage of this critical agricultural resource being supplied by such few countries, critical agricultural needs are exposed to significant risk from potential distribution failures. Such nontrivial risks increase the importance of the need to explore alternative fertilizer choices, given that much of the world's food supply relies on potassium fertilizer inputs.

Adding to the problem of risk exposure are cost concerns. Energy costs are rising worldwide due to instability of the distribution of natural resources. With instability in energy costs, even a marginal increase in the price of transportation of fertilizer is detrimental to all producers, and is likely to eliminate those producers who are only marginally profitable.

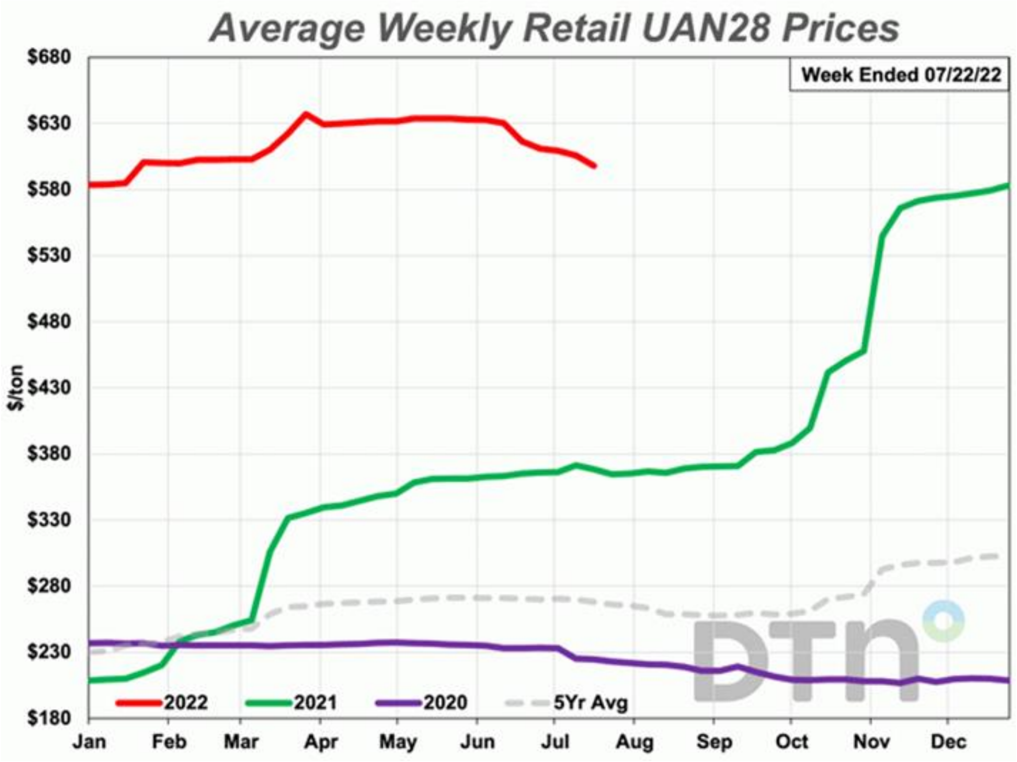

Figure 3.1: Cost of Urea Fertilizer from 2020 through July 22, 2022. (Quinn, 2022).

Recently, farmers have seen drastic increases to their variable costs due to the sharp increase of the price of nitrogen fertilizers. Compared to the price one year ago, 28% Urea ammonium nitrate (UAN28) is 64% higher, 32% urea ammonium nitrate (UAN32) is 66% higher costs, and anhydrous ammonium is 95% higher in price (Figure 1; Quinn, 2022). Such drastic changes in such a short time frame to required input costs have been detrimental to the livelihood of many farmers.

Another example of how changes in fertilizer cost can disrupt the food supply can be seen in current times with potash. The amount of potash produced in Africa is negligible. During the first half of 2022 it is estimated that West Africa is paying 250% higher costs compared to 2021 for potash, which must be imported from Canada, as a result of Western sanctions placed on Russia (Payne, 2022). Potash reserves in Canada require high transportation costs to Africa, as well as to many other parts of the world, given Canada’s less centralized geographical location. Such increases in fertilizer transportation costs are an example of how a highly asymmetric concentration of fertilizer distribution can disrupt food security (Production and Use of Potassium, 1998). The exploration of alternative fertilizers, such as polyhalite, opens up the opportunity for potassium to be supplied more regionally in areas where those reserves are present.

Although Potash is a widely used and reliable source of potassium (Manning, 2015), the potential benefits from a more diverse set of fertilizer options warrant exploring, including the efficiency and the effectiveness of these products within different cropping systems. A study conducted by Bhattarai & Swarnima, (2016) in Nepal demonstrated that different sources of potassium can affect the nutritional value of a crop. Bhattarai found that there were notable marketable differences between potato tubers grown using a Muriate of Potash (MOP) as opposed to Sulfate of Potash (SOP). Notably, MOP increased vitamin C content more than SOP and the type of potassium fertilizer used affected the sugar content of the potato crop. Ultimately, this study showed differing impacts of the fertilizers depending on parameters being measured.

The diversification of fertilizer inputs has the potential to improve the quality of the food system (Bowen et *al*., 2020). Fertilizer sources can influence not only the nutritional value, but also even taste preferences. Researchers in Sao Paulo, Brazil, evaluated differences in potassium sources for potatoes (*Solanum tuberosum*). Mello et al. (2018) found that polyhalite increased yields or no negative effect on yields of potatoes when compared to MOP and SOP. In this same study, some nutritional and flavor quality differences were evaluated among the control, MOP, SOP, polyhalite, and ammonium phosphate (MAP) treatments. This study found that in higher application rates, polyhalite increased dry matter, starch content, potato hardness and crunchiness compared to the other treatments.

In light of the motivation to assess alternative fertilizer sources, this paper explores the effectiveness of polyhalite as a nutrient base. Polyhalite is a mineral salt composed of potassium sulfates, calcium, magnesium, and traces of sodium chloride, boron, and iron (Yermiyahu et al., 2017). This mineral is likely formed through the evaporation of seawater (Gong et al., 2021). The use of polyhalite as a source of potassium fertilizer dates back to the 1930s before MOP was widely available (Barbier et al., 2017). Potash reserves were derived from Western Texas and New Mexico in the US. Although there are polyhalite reserves located in Poland, India, and Russia, currently, the only operational polyhalite mine can be found in one geographical location; off the North Yorkshire coast in the UK. Polyhalite has been studied as a potential fertilizer source of potassium, due to the mineral's appreciable concentration of K at 14% (Mello et al., 2018). The polyhalite mineral provides unique advantages as a fertilizer because the potassium, sulfur, calcium, and magnesium contents comprise four essential nutrients that plants require in high concentrations. Furthermore, the particular molecular ratio of polyhalite, K: Ca: Mg: SO4 at 2:2:1:4, is believed to provide certain benefits to plants (Yermiyahu et al., 2017). Polyhalite is considered to have high purity with less than 5% traces of sodium chloride, boron, or iron influencing purity (Yermiyahu et al., 2017).

Different crops require different nutritional needs. Polyhalite as a source of fertilizer can provide advantages because of the specific ratio of the nutrients present in the mineral. For example, Ozkan et al. (2018) found that polyhalite was effective in onion production. This is because onions require potassium and sulfur in ratios that are similar to the mineral makeup of polyhalite. Other crops that require high sulfur and some quantities of Mg, Ca, and K may benefit in a similar manner as seen by Ozkan et al. (2018).

Conventional fertilizer programs often require that the minerals contained in the polyhalite be applied as separate salts. There could be logistical and time benefits in the acquisition and application of a single fertilizer as opposed to multiple fertilizers. High-rate applications of potassium can be lost due to leaching in sandy textured soils and in areas of high rainfall rates, while split applications are less likely to suffer loss (Correa et al., 2018; Yermiyahu et al 2017). According to the same study, high-rate applications can also cause other soil fertility issues, such as salinization and cationic imbalance. Such losses due to leaching will affect the crop yields whenever the decreased potassium levels fail to meet the plant's requirements. A study conducted by Yermiyahu et. *al* (2017) found that the use of polyhalite was more effective in supplying the plant nutrients K, Ca, Mg, and S than when those nutrients were applied as separate salts. While multiple applications of a smaller dose of fertilizer is one solution to mitigating leaching, a single application of a fertilizer that slowly releases potassium is another possible solution. Differences in plant acquisition of those nutrients supplied may have been derived from differences in solubility. A single application of a fertilizer is often preferable to producers as it minimizes labor, time and fuel costs. Polyhalite mineral provides a slow release of nutrients K, Ca, Mg, and S because this mineral is less water soluble than most other conventional fertilizer sources such as potash (Barbarick, 1991). A slower release of the minerals can reduce leaching, providing a more efficient uptake of the fertilizer applied, improve K synchrony with crop K demands and reduce environmental externalities. Barbarick et al. (1991) found in a greenhouse study that the application of polyhalite, compared to soluble sulfate sources of K, Mg, and Ca, reduced leaching in a sandy loam soil. A finely ground polyhalite treatment even produced larger dry matter yield, and greater sulfur and potassium plant uptake response. This study suggests that the solubility of finely ground polyhalite mineral may provide advantages to crops grown in sandy textured soils. This study also implies that polyhalite is more beneficial than soluble fertilizers in acidic soil environments. Polyhalite minerals, and other less soluble minerals specifically do well in acidic soils because acidity can aid in the release of nutrients from the mineral by increasing solubility. The release of the plant available nutrients from the polyhalite is still at a slower rate than the quick release of a soluble fertilizer, such as potassium chloride, due to the differences in solubility. When evaluating the solubility of polyhalite, Huang et al. (2020) found that polyhalite behaved as a prolonged availability fertilizer with more nutrients retained in the top soil layer and not leached below the root zone (Huang et al., 2020).

Another potential advantage of polyhalite could stem from its benefit to crops sensitive to chlorine. One of the most common potassium fertilizers used in agriculture is potassium chloride. This fertilizer is comprised of 49.8-51.9% K and 49.8-51.9% Cl. Chloride at high levels is known to cause decline in plant vigor, necrosis and chlorosis in leaves, and stunted growth. These negative occurrences due to chloride and other salts are known as salt injury. Salt injury can occur at varying chlorine dosages depending on the salt tolerance of a crop. While the chloride tolerance of potatoes is still debated, some evidence suggests that polyhalite may be advantageous over MOP due to differences in chloride concentrations between fertilizers, MOP having much higher chloride amounts (Mello et al., 2018). In the same potassium study conducted in Southeast Brazil, Mello et al. (2018) attribute differences in yields and quality of potatoes to the differences in chlorine and magnesium present in polyhalite and MOP. When evaluating differences between potassium fertilizers in total salts by looking at salt index (SI), Barbier et al. (2017) found that MOP had a greater SI than SOP, and polyhalite had a lower SI than both SOP and MOP. Polyhalite had a SI of about half of what MOP had tested. This shows that polyhalite may be advantageous over MOP and SOP when used in soils with an already high electrical conductivity (EC).

Sweet potatoes are a common and important food source, whose primary nutrient intake requirement is potassium. The application of alternative potassium fertilizer choices in our study is on sweet potato crops. Recommended application rates of potassium for sweet potato production are estimated to be around 125-135 kg K ha^{-1} (Philips et al., 2005), and even can exceed 300 kg K ha^{-1} in soils with low initial levels of potassium. Sufficient quantities of potassium are necessary for maximum marketable sweet potato production. Potassium increases yield by increasing the proportion of dry matter diverted to root production, thus increasing size and quality (Bourke, 1985). Deficiency in potassium can result in decreased yields and decreased root quality as potassium is necessary both for carbohydrate formation and for carbohydrate translocation to the plant's roots (Correa et al., 2018). Higher potassium applications are associated with higher carbohydrate concentrations (Bhattarai, 2016). Because potassium is notably vital to sweet potatoes, any potential effects of alternative sources of potassium fertilizer such as polyhalite are likely to be observed. Tang et al. (2015) studied potassium deficiency in sweet potato production. This study found that deficiency in potassium significantly decreased total biomass, yields, photosynthetic efficiency, and chlorophyll content. These measured effects are a result of the acute damage caused to chloroplast ultrastructure associated with leaf chlorophyll biosynthesis and photosynthate accumulation, and also the disturbed protective enzymes involved in the antioxidative defense system when potassium is not supplied in necessary amounts (Tang et al., 2015).

Sweet potatoes are a critical element in the world's food supply (Bovell-Benjamin, 2007). Sweet potatoes are considered a staple crop as a vital source of calories in many parts of the world including many indigenous populations in Central and South Americas, Ryukyu Island, Africa, the Caribbean, the Maori people, Hawaiians, and Papua New Guineans (Bovell-Benjamin, 2007). There are advantages of using sweet potatoes as a staple food crop when compared to other staple crops around the world due to their high vitamin A and beta-carotene content. In fact, sweet potatoes contain 1487 IU vitamin A per 100g portion, while other staples such as rice, wheat, and sorghum contain 0 IU (Nutrition is an Essential Part of Child Development, 2022). Sweet potatoes are also an essential component of North Carolina crop production. Sweet potatoes are grown on 63454 ha in 2020 in the US valued at $726.18 million, and 60% of the acres grown were in North Carolina (Agricultural Marketing Resource Center, 2021). Sweet potatoes thrive in humid and hot growing conditions. North Carolina is suitable for such extensive sweet potato production due to frequent precipitation, temperature, and humidity conditions. North Carolina is also a suitable state for sweet potato production due to the sandy soil texture that resides within the coastal plain areas of the state. There are a variety of cultivars that are grown in North Carolina that vary in color, sugar, and disease resistance and include: Orleans, Evangeline, Bayou Belle, Beauregard, and Bonita. However, the most commonly grown variety is the Covington (Daughtry & Gaster, 2021).

Despite the considerable market for sweet potatoes, regional research examining potassium requirements for sweet potato production is remarkably limited. Many of the studies that provide information about sweet potato production are thirty years old. With the creation of newer cultivars, such as the Covington Sweet Potato, and other innovations and changes to production, there is still much to learn with regards to sweet potato productivity and quality. This study aims to contribute to the understanding of this issue by evaluating the use of polyhalite fertilizer in sweet potato production by comparing yields, soil nutrient levels, and nutrient uptake to varying rates of MOP fertilizer.

Materials and Methods

Treatment and Experimental design

This study was conducted at two site locations during the 2019 and 2020 growing seasons. Studies were conducted at the Cherry Research Station located in Goldsboro, North Carolina and the Lower Coastal Plain Research Station in Kinston, NC. Soil at the Goldsboro location was a Norfolk sandy loam (loamy, kaolinitic, thermic, Arsenic Kandiudults) and a Goldsboro loamy sand (fine-loamy, siliceous, subactive, thermic Aquic Paleudults) in the Kinston location. Soybean was the previous crop grown at both locations. In mid-May the land was prepared for planting with disking and bedding. Soils were bedded on 106 cm width rows. All sites had soil potassium index values recommending an addition of 112 kg K_2O ha^{-1} application rates based on the North Carolina Department of Agriculture (NCDA) soil testing service (North Carolina Department of Agriculture and Consumer Services, 2013). Soils at the field site were fumigated for pest control with dichloropropene using Telone II on 28 May 2019 at 94 l ha^{-1} and on 13 May 2020 with 75 l ha^{-1}. On 12 June 2019 and 1 June 2020 Flumioxazin applied as Valor and dipropylthiocamamate applied as Eptam were applied as pre-emergence to manage weed populations at rates of 175 g ha^{-1} and 1.5 pint ha^{-1} respectively. Before sweet potato planting, chlorpyrifos was applied as an insecticide, and mid-season, bifenthrin was applied.

The study was arranged as a randomized complete block design with four blocks. The treatments included increasing rates of potassium with two fertilizer sources: MOP and polyhalite. The MOP has a K_2O concentration of 60%. The natural mineral composition of polyhalite in this study was 14% K_2O, 48% SO_3, 6% MgO, and 17% CaO. Application rates included 25%, 50%, 100% (126 Kg K ha^{-1}) and 150% of the crop K requirement (Philips et al., 2005). Three zero K controls were also included in this study. These controls included no added fertilizers, a control with 0 kg K ha^{-1} but a full application of N fertilizer (80 kg N ha^{-1}), and lastly, a control with a 0 kg K ha^{-1} a full application of N fertilizer, and sulfur fertilizer equivalent to the amount added from the polyhalite fertilizer at 100% application rate (Table 1). The controls with N and N+S were used to evaluate the site responsiveness to these macro and secondary nutrients and allow for some inferences to their relative importance on sweet potato yield compared to the K. A second 100% MOP treatment was included that also contained the equivalent amount of the S, Mg, Ca that would be found in the 100% Polyhalite application rate (Table 1). This again was chosen to gain inference on the relative importance of the micronutrients on sweet potato yield rather than the potassium coming from the respective fertilizer. Nitrogen fertilizer as urea was applied to all MOP and polyhalite treatments at 100% of the recommended rate (80 kg N ha^{-1}). Each fertilizer treatment was weighed out by individual rows to maintain an even application. Fertilizers were applied on the top of the row by hand between 10 and 14 days after sweet potato slips were planted. The K fertilizer treatments and background nitrogen urea fertilizers were applied in one application on the same day. Fertilizers were incorporated after application through cultivation within the same day of application to prevent any nitrogen loss via volatilization. Sweet potatoes were planted at both sites on June 14, 2019 and June 4, 2020 at Kinston and June 5th 2020 at Goldsboro at 30 cm in row spacing.

Table 3.1: Fertilizer Treatments include controls and varying rates of polyhalite and muriate of potash (MOP).

Treatment	% K rate	K	S	Mg	Ca
			kg ha^{-1}		
Control	0%	0	0	0	0
Nitrogen Control	0%	0	0	0	0
Nitrogen + Sulfur	0%	0	0	0	0
Polyhalite	25%	32.5	51.7	9.8	32.3
	50%	62	103.3	19.6	64.6
	100%	126	206.6	39.15	129
	150%	188	310	58.7	193.6
MOP	25%	32.5	0	0	0
	50%	62	0	0	0
	100%	126	0	0	0
	150%	188	0	0	0
MOP + nutrients	100%	126	206.6	39.15	129

Soil Samples were collected at day 0, 30, 60, 90 days after planting and at harvest in 2019 and in 2020 the day 90 was missed due to constraints of field sampling with limited staff and accessibility due to Covid. Samples were taken at 5 points across the bed at low slope, mid slope, and center. This was done three times for a total of 15 samples per experimental unit at a depth of 15 cm. Samples were homogenized and were stored in a freezer at -4 °C until processed. Mehlich III extractions were performed on the soil samples at a 1:10 ratio of solution to soil. Two grams of air dried soil were added to Mehlich III solution and shaken for 5 minutes before the extractant was filtered. The extractant was analyzed for K, S, Mg, Ca using inductively coupled plasma optical emission spectrometry (ICP-OES) method (*SW-846 Test Method 6010D: Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES),* 2018). Tissue sampling of sweet potatoes occured 30, 60, and 90 days after planting. Tissue samples were dried in a ventilated oven at 60 degrees Celsius and analyzed for K, S, Mg, and Ca.

After harvest, sweet potatoes were graded. Sweet potatoes were graded based on USDA standards (Sweet Potatoes Grades and Standards, 2022). The jumbos (U.S. Extra No.1), U.S. No.1, U.S. No 2, and culls were separated and weighed. Petites were considered as U.S. No 1 and separated accordingly. Each grade was weighed on the same day. Sweet potatoes were stored for no more than a week before they were analyzed for nutrients. Eight randomly selected harvested No. 1 from each treatment was collected and a center piece 5 cm thick was diced and dried from each of the eight sweet potatoes. Harvested sweet potato roots were analyzed for K, S, Mg, Ca uptake following a digestion procedure for analysis on the ICP-OES

Statistical Design

All statistical analysis was conducted through SAS 9.3 software (Cary, NC, USA). Two approaches were employed for the statistical analysis for yields, yield quality distribution and root nutrient concentrations. Firstly, an ANOVA was conducted for all treatments using PROC GLIMMIX. We considered year and location as a combined factor termed environment (location x year). Environment was used in the random statement to allow for broader interpretation of the data beyond the individual field sites as the goal of this project was to provide producers with actionable recommendations on the use of polyhalite in the sweet potato growing region of NC. Block was also included in the random statement. Treatment was considered the fixed effect. Treatment was considered significant at $P<0.05$. If significant, a least-squared mean analysis was conducted using a Tukey's HSD test. In addition, contrast statements were generated to compare the multiple controls to evaluate if other controlling factors other than potassium have an impact on yield. Lastly, a contrast statement was used to compare the MOP treatment at 100% recommendation to the MOP treatment at 100% + micronutrients to evaluate potential yield gains due to the micronutrients. The second approach analyzing the crop response to increasing rates of potassium was to evaluate using regression. This again uses the PROC GLIMMIX procedure, where now the rate of application is a continuous variable and the source of K (Poly vs MOP) is a fixed factor. Replication and environment were considered random. The highest order polynomial and interaction that was significant was considered the best regression to describe the phenomena measured. In this analysis MOP 100% micronutrients were not considered and the control with N applied was considered the zero rate control. Soil sample and plant tissue data were analyzed as a repeated measures. In the case of the soil and plant data we analyzed the data by location and year due to unbalanced sampling frequency between the two years. The treatment was considered significant at $P<0.05$. If significant, a least-squared mean analysis was conducted using a Tukey's HSD test.

Results and Discussion:

Yield Response to Potassium Treatments

The only significant difference in marketable yields among treatments was the polyhalite treatment at 100% recommended K produced higher yields (39.5 t ha^{-1}) than the control + sulfur (CNS) (30 t ha^{-1}; Table 2). In the remaining treatments there were no significant differences in total marketable yields among potassium fertilizer treatments and MOP treatments, control, or nitrogen control (CN) at any of the rates (Table 2). There was no difference when adding micronutrients to the MOP to MOP alone at the 100% rate. For total root biomass the same pattern was present with only Poly 100% greater than the control+N+S. A quadratic relationship between total marketable yield and K rate was observed ($P < 0.05$; Figure 2). No differences were observed between K source nor a significant interaction between K source and rate ($P > 0.05$). Marketable yields increased until approximately 103 kg K_2O ha^{-1}, after which yields declined.

Table 3.2: Marketable yields and total root biomass over the four site years (2019, 2020, Goldsboro and Kinston). Contrast statements include comparison of controls and the MOP at 189 kg K2O ha-1 vs MOP with equivalent micronutrients of polyhalite at the same rate of K2O.

Treatment	Rate	Marketable Yields†	Total Root Biomass
	(kg K_2O ha^{-1})	(t ha^{-1})	(t ha^{-1})
Control	0	31.5 (2.6) ab	31.9 (2.6) ab
Control + Nitrogen (CN)	0	32.6 (2.3) ab	32.8 (2.3) ab
Control + N & Sulfur (CNS)	0	30.0 (2.3) b	30.2 (2.4) b
Polyhalite	31.5	31.7 (2.0) ab	31.9 (2.0) ab
	63	35.2 (2.3) ab	35.4 (2.3) ab
	126	39.5 (2.4) a	39.9 (2.3) a
	189	35.1 (2.7) ab	35.3 (2.7) ab
Muriate of Potash	31.5	34.3 (2.8) ab	34.4 (2.8) ab
	63	35.6 (1.7) ab	35.8 (1.7) ab
	126	37.1 (2.2) ab	39.0 (3.1) ab
	189	36.4 (2.4) ab	36.5 (2.4) ab
MOP + nutrients	189	35.3 (2.7) ab	36.1 (2.4) ab
Statistics		**Pr>F**	
Treatment		0.0279	0.0142
Contrasts			
Control vs CN		n.s.	n.s.
Control vs CNS		n.s.	n.s.
CN vs CNS		n.s.	n.s.
MOP vs MOP+nutrients		n.s.	n.s.

†Marketable Yields = Jumbo, US #1 and Canner classifications

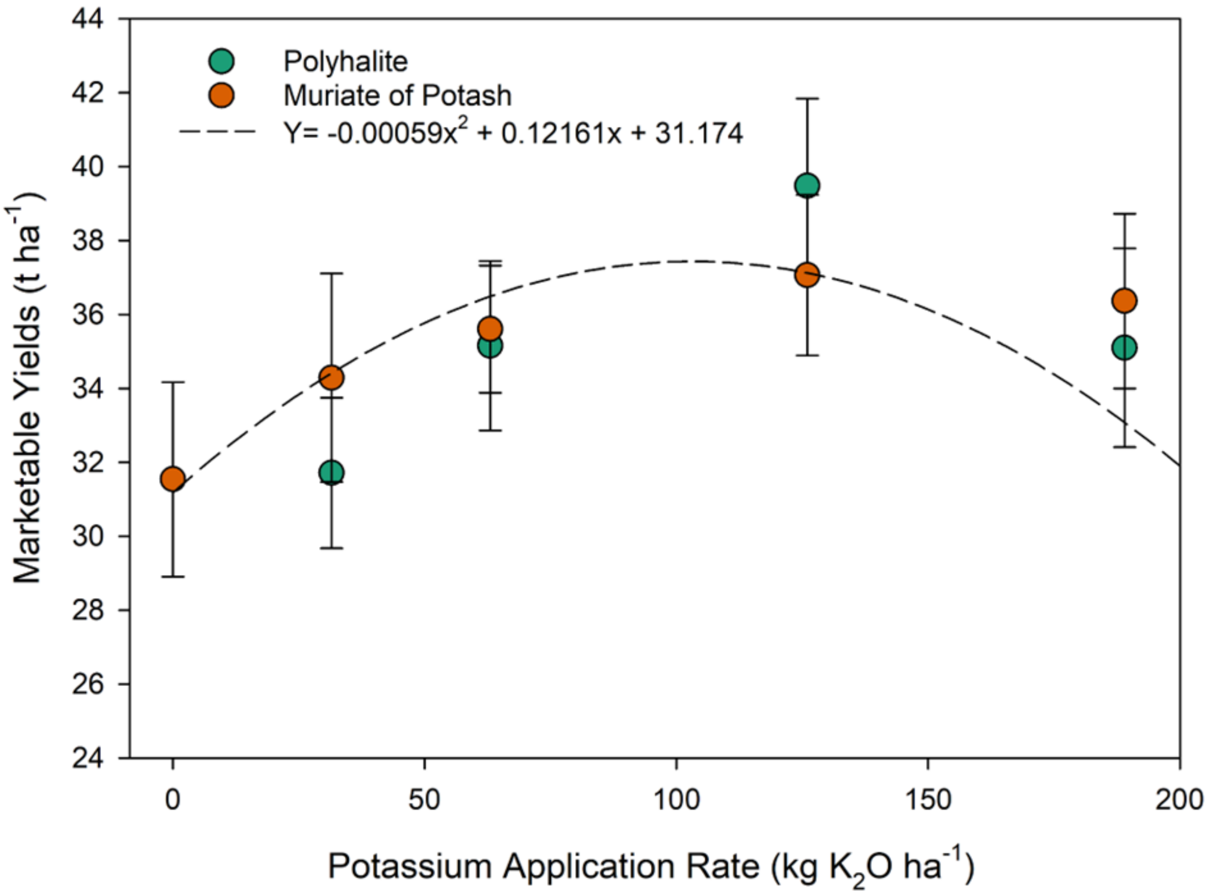

Figure 3.2: Quadratic regression of marketable yields over the four site years (2019, 2020, Goldsboro and Kinston). Single regression of rate only as fertilizer source (polyhalite and muriate of potash) was not significant.

Many nutrient response studies in sweet potatoes see no response with additional nutrients supplied beyond rates of 28 kg ha^{-1} (Phillips et al., 2005). However, some studies attribute dry matter production to the presence and concentration of potassium (Tsuno & Fujise, 1964). Potassium contributes to higher photosynthetic rates within the leaves (Tsuno & Fujise, 1964). But there are other environmental factors that dictate root storage to a greater extent. For example, the number of storage roots that can be formed is dictated by early water availability (Villordon et al., 2012). Without the necessary environmental conditions that are required to produce more storage roots, fertilization rate may not be an influencing factor on yields. Higher fertilization rates may be more useful when such environmental conditions described are met. Because the nutrient dynamics in sweet potato are so complex, future research may benefit from exploring nutrient environmental interactions on sweet potato growth. Further understanding on the extent at which environmental stressors influence nutrient demands in sweet potato could aid in the development of consistent and accurate recommendations. Lastly, initial soil potassium status in the spring may have a controlling effect on the magnitude of response to additional fertilizer application.

Distribution of Grades

There were no significant differences among treatments when evaluating the number of No. 1 or culls by % total yield. This implies that fertilizer treatments do not influence the weight of number ones produced in proportion to the total weight of harvested sweet potatoes. However, there were significant treatment effects of the proportion of jumbos and canners by weight. At higher polyhalite application rates (100% and 150%), there were larger proportions of jumbos by weight and smaller proportion of canners by weight when compared to the control (Table 3). Such findings imply that there are interactions between the nutrients supplied by the polyhalite and how energy stored is distributed within the plant. Typically dry matter production in sweet potatoes is governed by potassium uptake (Tsuno & Fujise 1964). But there were no differences in treatments in potassium uptake or potassium concentrations.

Table 3.3: Relative proportion of total root biomass by quality category (Jumbo, US #1s, Canner and Cull) over the four site years (2019, 2020, Goldsboro and Kinston).

Contrast statements include comparison of controls and the MOP at 189 kg K2O ha-1 vs MOP with equivalent micronutrients of polyhalite at the same rate of K2O.

Treatment	Rate	Jumbo	Ones	Canner	Cull
	(kg K_2O ha^{-1})	% of Total Yield			
Control	0	25.7 (4.2) b	55.7 (3.3)	17.3 (4.1) a	1.3 (0.5)
Control + N	0	40.7 (4.3) ab	48.2 (3.6)	10.4 (2.0) ab	0.6 (0.2)
Control + N & S	0	33.6 (4.5) ab	53.4 (3.7)	12.2 (1.9) ab	0.8 (0.5)
Polyhalite	31.5	40.0 (5.5) ab	49.0 (4.3)	10.4 (1.7) ab	0.6 (0.2)
	63	37.2 (4.4) ab	51.26 (3.1)	10.9 (1.7) ab	0.6 (0.2)
	126	44.4 (4.9) a	44.9 (3.2)	9.5 (2.2) b	1.2 (0.5)
	189	43.2 (4.1) a	48.1 (3.6)	8.0 (1.0) b	0.6 (0.3)
Muriate of Potash	31.5	43.4 (5.5) a	42.6 (3.9)	13.4 (4.0) ab	0.5 (0.2)
	63	46.1 (4.5) a	45.1 (4.3)	8.3 (1.4) b	0.5 (0.2)
	126	43.1 (4.8) ab	46.1 (4.1)	7.9 (1.3) b	1.2 (0.5)
	189	42.7 (4.3) ab	46.3 (3.1)	10.4 (1.7) ab	2.9 (2.2)
MOP + nutrients	189	34.7 (4.3) ab	51.2 (4.2)	10.8 (2.2) ab	3.2 (2.9)
Statistics		**Pr>F**			
Treatment		0.0072	n.s.	0.0056	n.s.
Contrasts		**Pr>F**			
Control vs CN		0.0051	n.s.	0.0037	n.s.
Control vs CNS		n.s.	n.s.	0.0297	n.s.
CN vs CNS		n.s.	n.s.	n.s.	n.s.

The differences between the proportions of root biomass by category may be attributed to another nutrient that is supplied by the polyhalite. Another possible explanation for these results is that there are differences in the rate of maturity due to treatments. Relative growth rate is highest when there is a higher K/N ratio (Tsuno & Fujise, 1964). Sweet potatoes in the treatment plots that contained higher K may have matured at a faster rate than the other treatments. As sweet potatoes mature, they enlarge. Because all treatments were harvested at the same time, sweet potatoes were more developed and in turn larger, in the plots with the higher growth rate.

Soil Nutrient Results

Another possible explanation for the lack of differences in yields among categorical treatments is that the potassium supplied by the fertilizer treatments is leached out to the environment. The soil the sweet potatoes were grown in was textured as sandy-loam in Goldsboro and loamy-sand in Kinston. These coarse textured soils often have difficulty holding on to mobile nutrients if organic matter content is low. Soil data was evaluated to determine if leachability of soil K might have influenced yields. Soil sample data collected at four dates throughout the growing season demonstrated how potassium concentration in the soil changed as the sweet potato crop reached maturity. Figure 3-6 show how K differed between fertilizer type and fertilizer rate. At Goldsboro 2019 and Kinston 2019 similar trends in soil K levels were seen. Initial soil test levels were below what is required for plant uptake. This led to differences between the higher rate treatments and the control at the end of the growing season, where high rates left more K in the soil (Figure 3 and 4). In Kinston, MOP 150% maintained 185 mg kg^{-1} at the end of the growing season as opposed to the control where only 96 mg kg^{-1} remained (Table 5). Goldsboro also saw this trend where MOP 150% maintained 149 mg kg^{-1} whereas the control maintained only 66 mg kg^{-1} (Table 6). The MOP 100% and MOP 150% rates provided a significantly larger amount of K in the soil than all the other lower rate treatments, as expected. At the second soil sampling date (about 30 days after fertilization), the MOP 150% was still significantly higher than all lower rate treatments except the MOP 100%. At the third sampling date (about 60 days after fertilization), the MOP 150% and MOP 100% once again contributed a larger amount of soil K than the other rates. At the last sampling date, completed days before sweet potato harvest, MOP 150% and MOP 100% were still significantly higher in soil K than all lower rate treatments. These results show that higher rates of MOP fertilizer initially contribute larger amounts of soil K. These results are consistent with expectations because more fertilizer applied typically results in higher nutrient levels in the soil. However, what is surprising about these results is that at the end of the growing season, soil K still varied among rates when soil test level is initially higher as seen in 2019 in both locations and in 2020 at Goldsboro (Table 5, 6, and 8). This suggests that sweet potatoes were not taking up all the K that was provided in the higher rate treatments. Differences between high rate treatments and the control, in the amount of K remaining in the soil at the end of the growing season, may be an indicator that leaching may not have been an influencing factor on yield differences remaining the same based on these trends seen in 2019

Table 3.4: Soil potassium samples taken throughout the growing season in Kinston 2019.Contrast statements include comparison of controls and the MOP at 189 kg K$_2$O ha^{-1} vs MOP with equivalent micronutrients of polyhalite at the same rate of K$_2$O.

Treatment	Rate	Kinston 2019 K (mg kg^{-1})			
		July 8th	July 24th	Aug 12th	October 24
		K (mg kg^{-1})			
Control	0	127 c	115 c	102 c	96 f
Control + Nitrogen (CN)	0	140 bc	131 bc	113 c	80 f
Control + Nitrogen & Sulfur (CNS)	0	136 bc	115 c	67 c	80 f
Polyhalite	31.5	156 bc	151 abc	123 c	103 ef
	63	138 bc	169 abc	170 bc	115 def
	126	164 bc	245 abc	287 ab	166 abc
	189	187 bc	261 abc	307 a	199 ab
Muriate of Potash	31.5	246 b	297 abc	172 bc	132 cdef
	63	214 bc	203 abc	181 bc	160 bcde
	126	376 a	257 abc	246 ab	185 abc
	189	448 a	357 a	305 a	223 a
MOP + nutrients	189	376 a	338 a	286 ab	184 abc
Statistics					
Treatment		<0.0001			
Sampling Time		<0.0001			
Treatment x Sampling Time		0.0001			

Table 3.5: Soil potassium samples taken throughout the growing season in Goldsboro 2019.Contrast statements include comparison of controls and the MOP at 189 kg K_2O ha^{-1} vs MOP with equivalent micronutrients of polyhalite at the same rate of K_2O.

Treatment	Rate	Goldsboro 2019 K (mg kg^{-1})			
		July 1st	July 24th	Aug 13th	Oct 18th
		K (mg kg^{-1})			
Control	0	117 cd	92 c	71 d	66 bc
Control + Nitrogen (CN)	0	80 d	90 c	60 d	59 c
Control + Nitrogen & Sulfur (CNS)	0	80 d	99 c	73 d	56 c
Polyhalite	31.5	98 d	147 abc	91 cd	79 bc
	63	112 cd	172 abc	110 bcd	81 abc
	126	138 cd	246 ab	162 abc	115 abc
	189	117 cd	205 abc	202 a	132 ab
Muriate of Potash	31.5	132 cd	141 bc	90 cd	74 bc
	63	164 bcd	141 bc	107 bcd	71 bc
	126	267 ab	220 abc	176 ab	111 abc
	189	320 a	284 a	207 a	149 a
MOP + nutrients	189	216 abc	252 ab	133 abcd	81 abc
Effects					
Treatment		<0.0001			
Sampling Time		<0.0001			
Treatment x Sampling Time		0.0001			

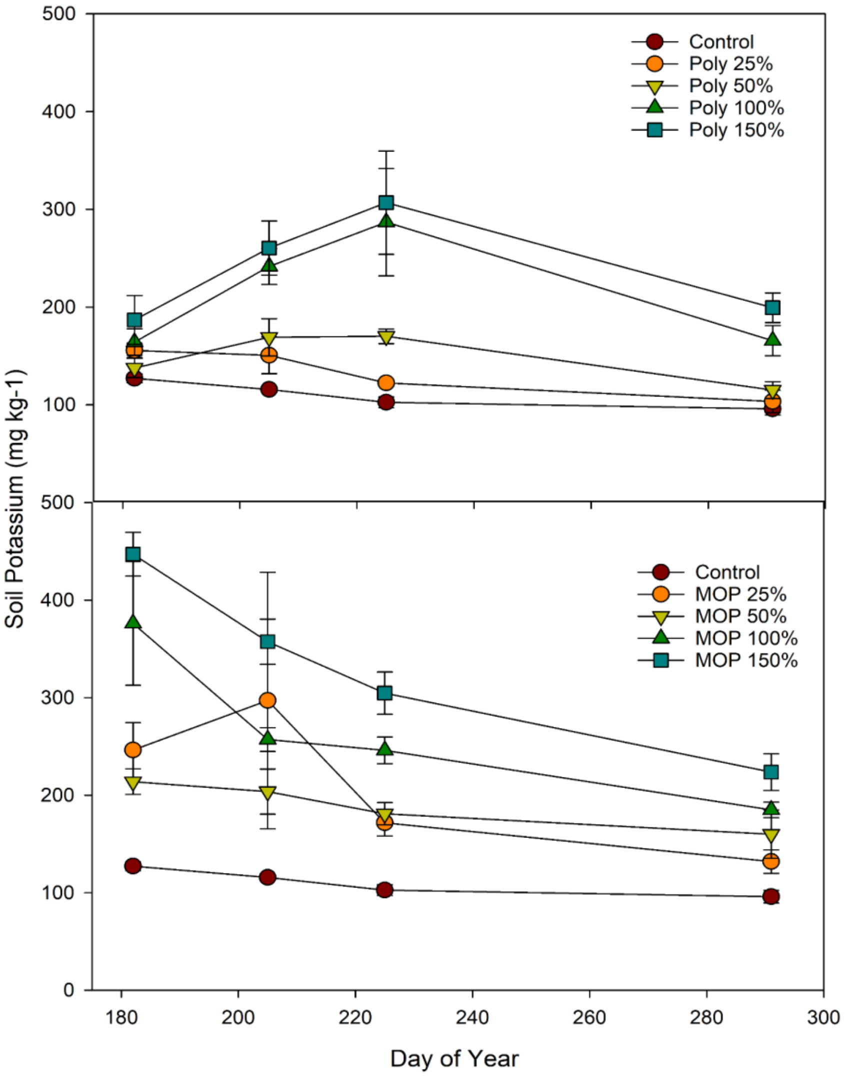

Figure 3.3: Potassium in the soil from fertilization to harvest at Kinston 2019. The top graph depicts the polyhalite fertilizer, and the bottom graph shows levels of potassium supplied by the MOP fertilizer rates

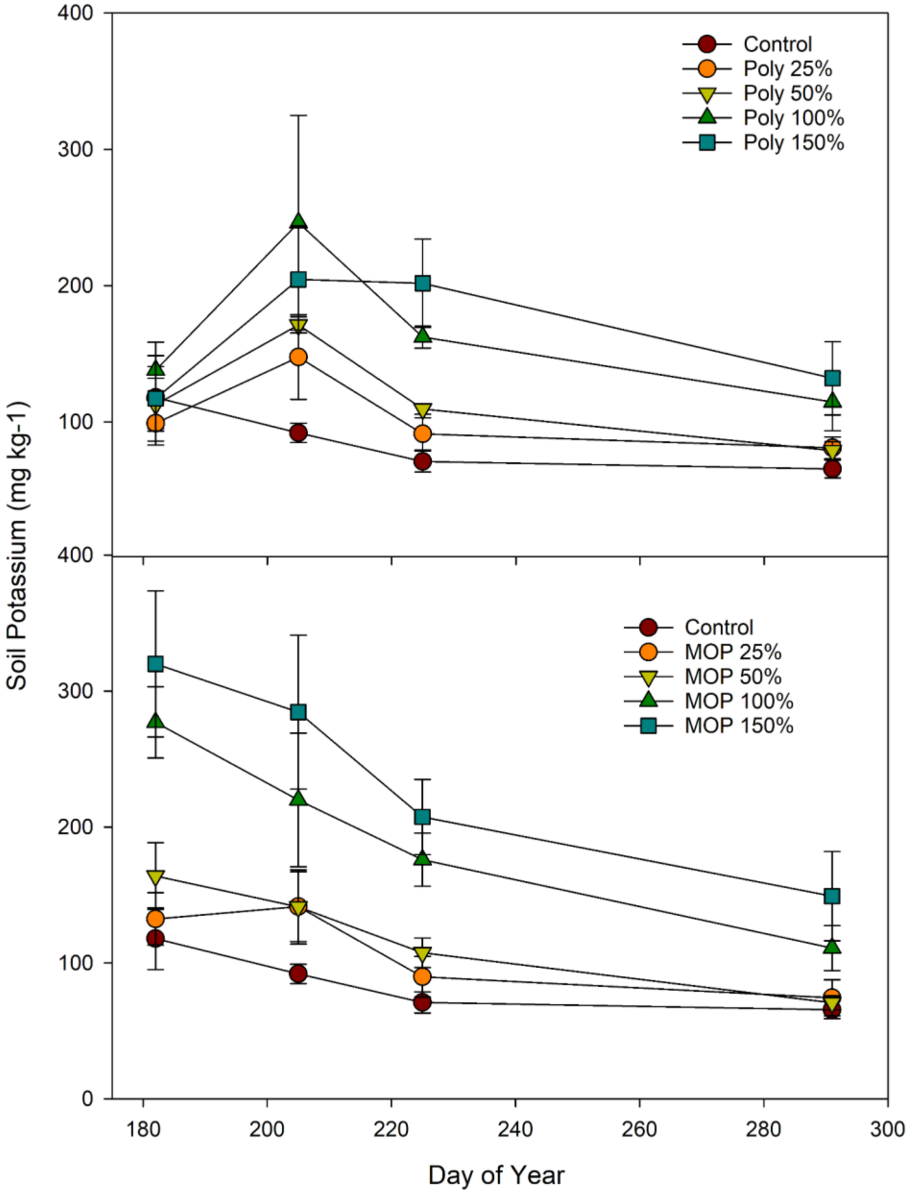

Figure 3.4: Potassium in the soil from fertilization to harvest at Goldsboro 2019. The top graph depicts the polyhalite fertilizer, and the bottom graph shows levels of potassium supplied by the MOP fertilizer rates

In 2020 Kinston, initial soil K values seen in the control were low at 50 mg kg^{-1} in the control (Table 6). Higher applications of MOP led to higher soil test K which was as high as 425 mg kg^{-1} at the first sampling date (Table 6). The polyhalite at the highest rate was tested to only contain 185 mg kg^{-1}. But by the end of the growing season, there were no differences in K among any of the treatments (Figure 6). This indicates that the potassium at this site was either lost to the environment through leaching, or taken up by the sweet potatoes as indicated by the low K index values across all of the treatments. More than likely, much of the potassium was taken up by the plant, indicated by the initially low soil K test levels.

Table 3.6: Soil potassium samples taken throughout the growing season in Kinston 2020.Contrast statements include comparison of controls and the MOP at 189 kg K_2O ha^{-1} vs MOP with equivalent micronutrients of polyhalite at the same rate of K_2O.

Treatment	Rate	Kinston 2020 K (mg kg^{-1})		
		July 5th	July 29th	Sept 22
Control	0	50 c	91 c	32 a
Control + Nitrogen (CN)	0	88 c	68 c	29 a
Control + Nitrogen & Sulfur (CNS)	0	52 c	43 c	50 a
Polyhalite	31.5	141 bc	126 abc	34 a
	63	122 bc	141 abc	43 a
	126	136 bc	264 abc	84 a
	189	184 bc	361 a	85 a
Muriate of Potash	31.5	104 c	87 c	40 a
	63	147 bc	112 bc	46 a
	126	353 a	260 abc	75 a
	189	425 a	347 ab	95 a
MOP + nutrients	189	270 ab	267 abc	67 a
Effect				
Treatment		<0.0001		
Sampling Time		<0.0001		
Treatment x Sampling Time		0.0001		

At Goldsboro in 2020, initial soil test K was much higher. The control tested for 148 mg kg^{-1}. The higher rate treatments such as the polyhalite at 150% and MOP 150% had significantly higher K remaining at the end of the season than the control and lower rate fertilizer treatments (Table 7, Figure 5). This indicates that plants did not uptake all of the K that was available when rates were highest, suggesting that both MOP and polyhalite at 150% recommended K are supplying more than is needed to the plant. This is a similar trend to what was described at both locations in 2019.

Table 3.7: Soil potassium samples taken throughout the growing season in Goldsboro 2020.Contrast statements include comparison of controls and the MOP at 189 kg K_2O ha^{-1} vs MOP with equivalent micronutrients of polysulfate at the same rate of K_2O.

Treatment	Rate	Goldsboro 2020 K (mg kg^{-1})		
		July 5th	July 30th	Sept 22nd
		K (mg kg^{-1})		
Control	0	148 d	122 de	81 bc
Control + Nitrogen (CN)	0	143 d	101 e	59 c
Control + Nitrogen & Sulfur (CNS)	0	164 d	96 e	64 c
Polyhalite	31.5	193 d	150 cde	69 c
	63	258 cd	188 cde	97 bc
	126	280 cd	291 bcd	147 abc
	189	385 bc	400 ab	218 a
Muriate of Potash	31.5	234 d	154 cde	76 bc
	63	281 cd	196 cde	70 c
	126	467 ab	323 abc	126 abc
	189	542 a	487 a	190 ab
MOP + nutrients	189	426 ab	267 bcde	95 bc
Statistics				
Treatment		<0.0001		
Sampling Time		<0.0001		
Treatment x Sampling Time		0.0001		

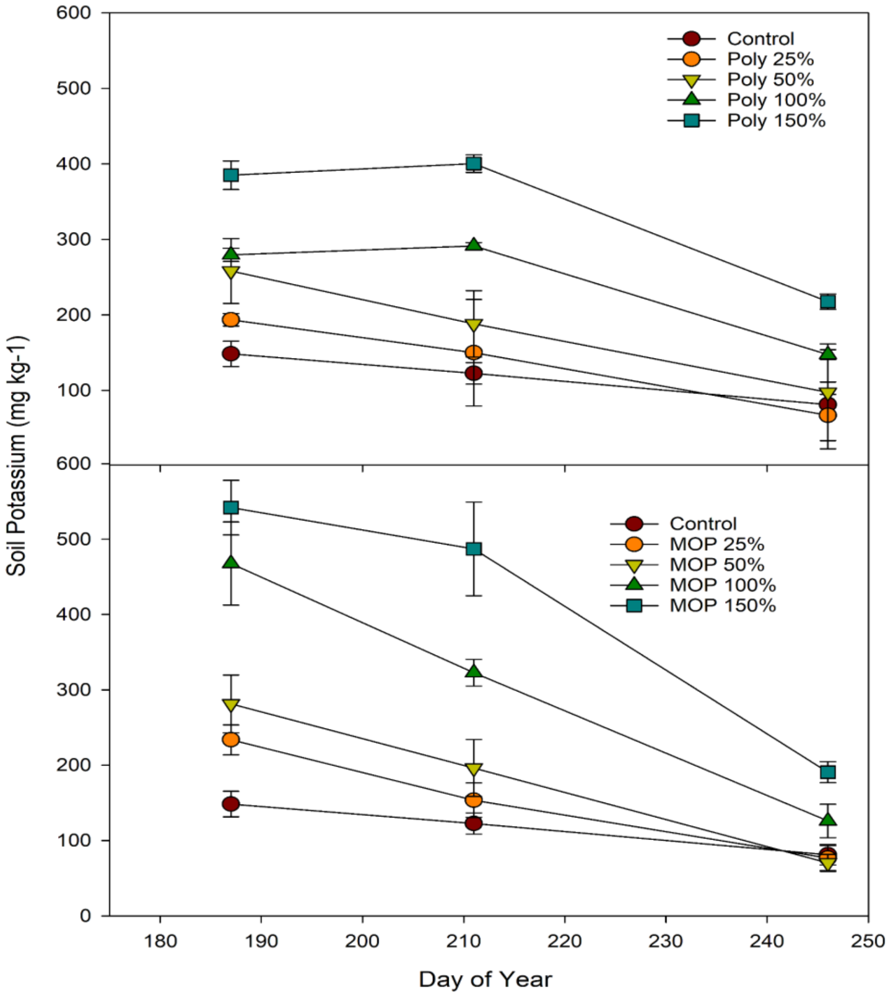

Figure 3.5: Potassium in the soil from fertilization to harvest at Goldsboro 2020. The top graph depicts the polyhalite fertilizer, and the bottom graph shows levels of potassium supplied by the MOP fertilizer rates

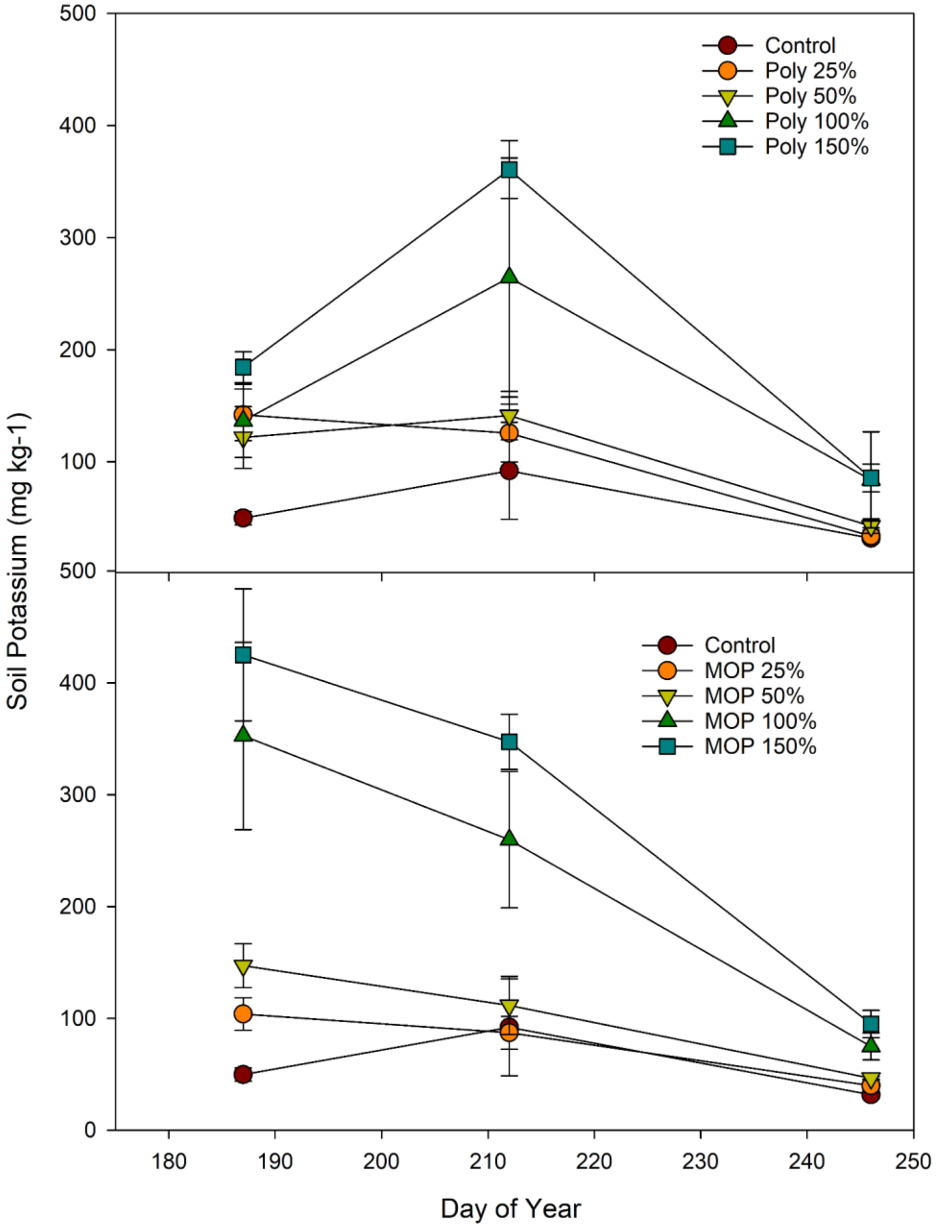

Figure 3.6: Potassium in the soil from fertilization to harvest at Kinston 2020. The top graph depicts the polyhalite fertilizer, and the bottom graph shows levels of potassium supplied by the MOP fertilizer rates

The release rate of the two sources were significantly different through time. In all instances the highest rates of MOP at the first sampling date showed significantly greater concentrations of K in the soil compared to POLY at the highest rate (Table 5-8). However, at the second sampling period the POLY treatments K concentrations were not significantly different to the equivalent MOP treatments. These differences in solubilization rates have important implications on K synchrony with crop K uptake. While there is limited research showing K uptake rates over time for sweet potatoes, Osaki et al. (1997) tracked uptake of K over time in sweet potato development. The sweet potato in this instance had maximum K uptake at ~50 days after planting. If this is a consistent pattern in North Carolina sweet potatoes then the slower release of the polyhalite may be advantageous in the long run. However, in this study, no such advantage was observed.

Differences in Nutrient Concentrations in Plant Tissue

Nutrient concentration of K, Mg, Ca, and S in harvested roots were measured. Root uptake of these nutrients in the soil was also measured. The evaluation of these two measurements can give us an understanding of where the applied nutrients are distributed between the harvested roots, the soil, and the environment. Accumulation of a nutrient in the soil can imply that the nutrient is either not needed by the plant or bound in chemical forms that are unavailable to the plant, but appear in soil tests. Accumulation of a nutrient in plant tissue can imply that the nutrient is either needed by the plant or stored in the roots for a later use. The differences between nutrient concentrations in the plant tissue and soil were found to vary by nutrient and treatment. Potassium accumulation in the root tissue increased as the rate increased up to an estimated application rate of 141 kg K_2O ha^{-1} when a quadratic regression was fit (Figure 7). However, as with marketable yield there was no significant differentiation between fertilizer sources.

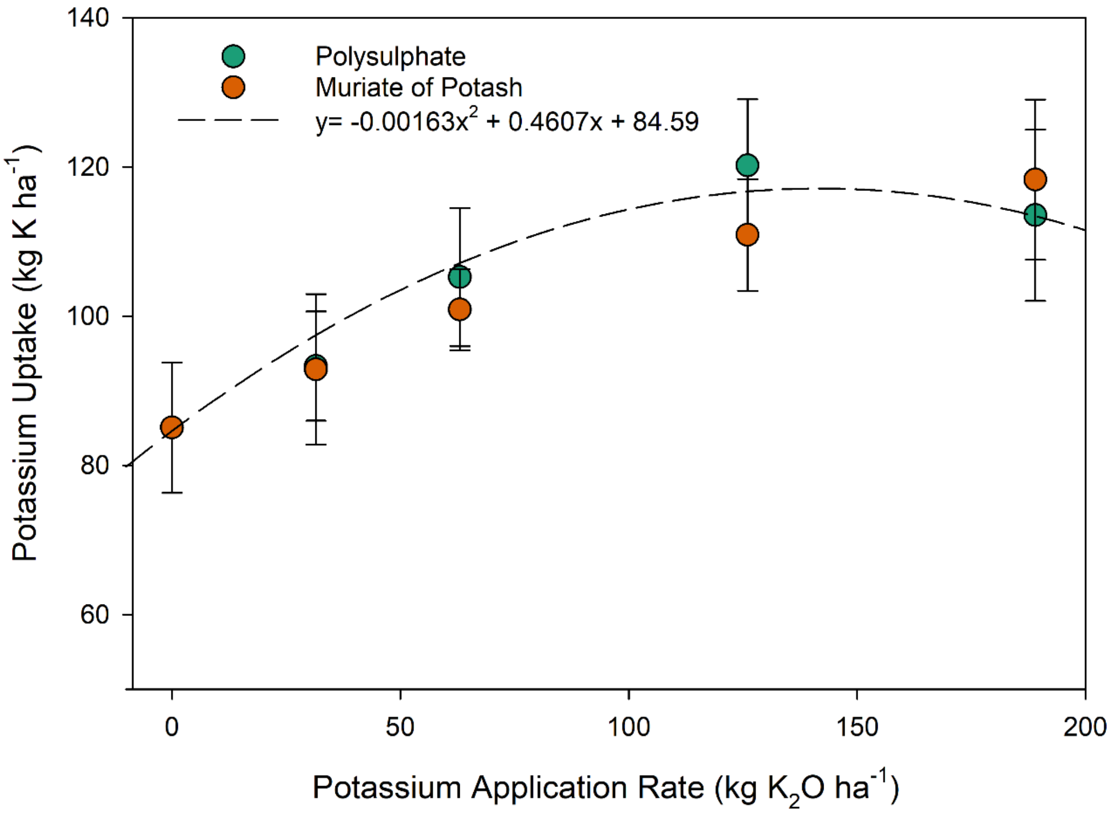

Figure 3.7: Quadratic regression of potassium root biomass uptake over the four site years (2019, 2020, Goldsboro and Kinston). Single regression of rate only as fertilizer source (polyhalite and muriate of potash) was not significant.

When treating variables as categorical, there were differences in K uptake among treatments in the MOP but not the polyhalite, but both had an increase in K uptake at high rates when compared to the control (Table 9). Concentration in the root did differentiate between potassium sources when the regression analysis was performed. With a source by quadratic rate as significant (P=0.0167; Figure 8). There was an upward increase in K concentration of the MOP and a decline at the highest rates for the MOP. This may be related to the significantly greater amount of available K in the early soil samples showing a faster release rate of the MOP than the polyhalite treatments.

Table 3.8: Potassium concentration and root biomass potassium uptake over the four site years.Contrast statements include comparison of controls and the MOP at 189 kg K2O ha-1 vs MOP with equivalent micronutrients of polyhalite at the same rate of K2O.

Treatment	Rate	Root Potassium Conce ntration	Root Potassium Uptake
	(kg K_2O ha^{-1})	(%wt)	(kg K ha^{-1})
Control	0	1.61 bcd	84.2 (9.1) cd
Control + Nitrogen (CN)	0	1.52 d	89.0 (8.0) bcd
Control + N & S (CNS)	0	1.53 d	82.0 (9.1) d
Polyhalite	31.5	1.66 abcd	93.3 (7.3) abcd
	63	1.69 abcd	105.2 (9.6) abcd
	126	1.71 abc	122.0 (8.9) a
	189	1.74 ab	113.5 (11.4) abc
Muriate of Potash	31.5	1.53d	92.9 (10.1) abcd
	63	1.59 cd	100.9 (5.4) abcd
	126	1.66 abcd	110.9 (7.4) ab
	189	1.81 a	119.6 (10.7) abcd
MOP + nutrients	189	1.8 ab	110.9 (10.7) abcd
Effect		**Pr>F**	
Treatment		<0.0001	<0.001
Contrasts			
Control vs CN		n.s.	n.s.
Control vs CNS		n.s.	n.s.
CN vs CNS		n.s.	n.s.
MOP vs MOP+Nutrients		0.0202	n.s.

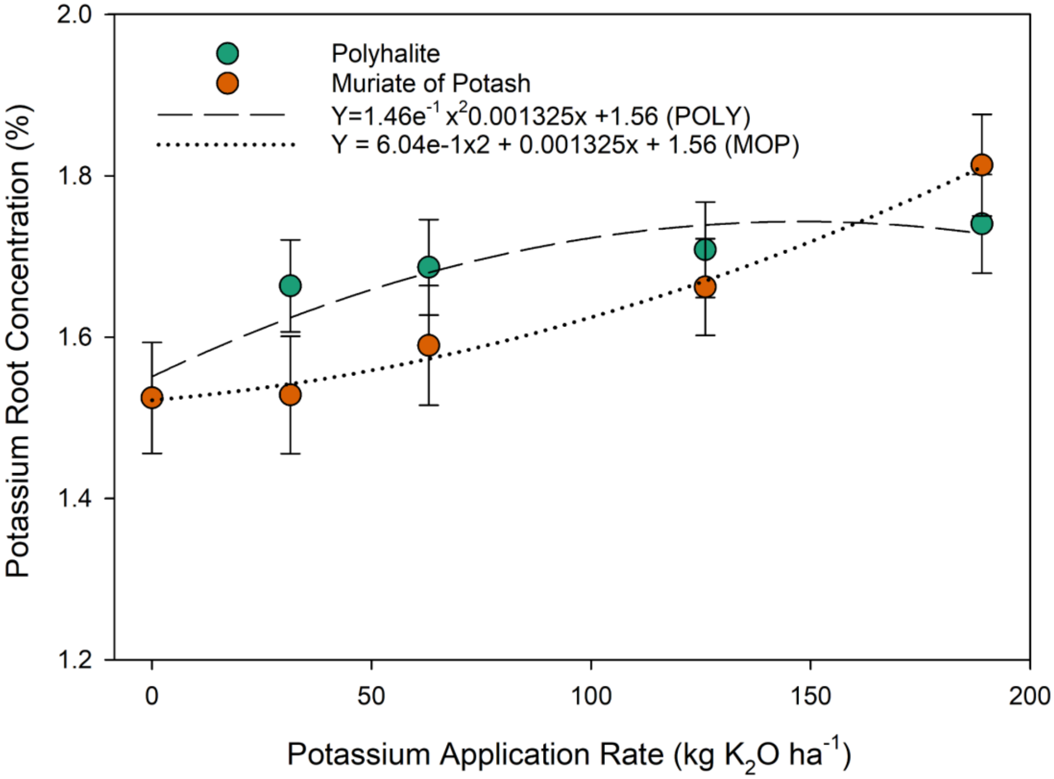

Figure 3.8: Quadratic regressions of root potassium concentration over the four site years (2019, 2020, Goldsboro and Kinston).

Potassium concentration in the leaf tissues did not vary between rates for the polyhalite or MOP treatments in 2019 at either location or in Goldsboro 2020 (Table 9). There were differences between K accumulation in the plant leaves in Kinston 2020. Kinston 2020 was also the location and year that had low initial soil K test levels seen in Table 6, which resulted in there being no differences among any treatments for K left in the soil at the end of the season. The three site years that contained statistically different soil K levels at the end of the growing season resulted in no difference between K accumulation in the plant leaf tissue. But the site year that had low initial soil K and ended the season with no difference between potassium levels, because more potassium was needed for plant uptake, did yield differences between some of the treatments in K concentration (Table 9).

Table 3.9: Potassium concentration in the leaf tissue samples taken throughout the growing season.Contrast statements include comparison of controls and the MOP at 189 kg K2O ha-1 vs MOP with equivalent micronutrients of polyhalite at the same rate of K2O.

Treatment	Rate	Kinston 2019	Kinston 2020	Goldsboro 2019	Goldsboro 2020
		(% K)			
Control	0	3.77 (0.26)	2.71 (0.35) bcd	3.53 (0.29)	3.00 (0.22) ab
Control + Nitrogen (CN)	0	3.62 (0.21)	2.81 (0.22) abcd	3.07 (0.28)	2.68 (0.15) b
Control + Nitrogen & Sulfur (CNS)	0	3.55 (0.22)	2.14 (0.24) d	3.23 (0.25)	2.84 (0.15) ab
Polyhalite	31.5	3.69 (0.21)	2.64 (0.18) bcd	3.43 (0.27)	3.03 (0.17) ab
	63	3.53 (0.23)	2.94 (0.22) abcd	3.27 (0.21)	3.06 (0.15) ab
	126	3.74 (0.19)	2.80 (0.23) abcd	3.52 (0.25)	2.87 (0.19) ab
	189	3.52 (0.18)	3.04 (0.20) abcd	3.28 (0.23)	3.12 (0.14) ab
Muriate of Potash	31.5	3.63 (0.20)	2.48 (0.21) cd	3.34 (0.29)	2.78 (0.12) ab
	63	3.77 (0.20)	2.88 (0.24) abcd	3.32 (0.25)	3.00 (0.21) ab
	126	3.74 (0.19)	3.69 (0.16) a	3.48 (0.24)	3.29 (0.21) ab
	189	3.63 (0.19)	3.48 (0.12) ab	3.59 (0.22)	3.43 (0.19) a
MOP + nutrients	189	3.84 (0.23)	3.43 (0.14) abc	3.26 (0.27)	3.15 (0.17) ab
Statistics		**Pr>F**			
Treatment		n.s.	<0.001	n.s.	0.0611*
Sampling Time		<0.0001	n.s.	<0.0001)	<0.0001

Table 2.9 (continued)

Contrasts	**Pr>F**			
Control vs CN	n.s.	n.s.	n.s.	n.s.
Control vs CNS	n.s.	n.s.	n.s.	n.s.
CN vs CNS	n.s.	0.0179	n.s.	n.s.
MOP vs MOP+nutrients	n.s.	n.s.	n.s.	n.s.

There were no differences among any treatments including the control in nutrient acquisition and soil concentration of calcium and magnesium (Table 10 and 11). The Mg and Ca in the soil at the start of the growing season was sufficient for plant growth. This is suggested by the root tissue data where the control with no added magnesium or calcium is equal in tissue nutrient concentration to all polyhalite treatments. There were no significant differences in Mg or Ca in soil among treatments when evaluating the percent calcium or percent magnesium by weight (Table 10 and 11). While the polyhalite treatments may be contributing some magnesium and calcium to the soil, there may be no differences between the polyhalite rates and the control because the amount of Ca and Mg provided from polyhalite mineral may be marginal compared to the extensive amount of these minerals residing in the soil.

Table 3.10: Calcium concentration and root calcium uptake over the four site years.Contrast statements include comparison of controls and the MOP at 189 kg K_2O ha^{-1} vs MOP with equivalent micronutrients of polyhalite at the same rate of K_2O.

Treatment	Rate	Root Calcium Concentration	Root Calcium Uptake
	(kg K_2O ha^{-1})	(%wt)	(kg ha^{-1})
Control	0	0.148 (0.01)	8.90 (0.9)
Control + Nitrogen (CN)	0	0.150 (0.01)	9.39 (0.9)
Control + N & S (CNS)	0	0.152 (0.01)	9.16 (1.1)
Polyhalite	31.5	0.158 (0.01)	9.59 (0.7)
	63	0.141 (0.01)	9.71 (1.0)
	126	0.154 (0.01)	12.0 (1.0)
	189	0.154 (0.01)	10.7 (1.0)
Muriate of Potash	31.5	0.160 (0.01)	10.9 (1.2)
	63	0.151 (0.01)	10.4 (0.7)
	126	0.155 (0.01)	11.5 (0.9)
	189	0.146 (0.01)	10.5 (1.2)
MOP + nutrients	189	0.149 (0.01)	10.4 (1.0)
Statistics		**Pr>F**	
Treatment		n.s.	0.0174
Contrasts			
Control vs CN		n.s.	n.s.
Control vs CNS		n.s.	n.s.
CN vs CNS		n.s.	n.s.
MOP vs MOP+nutrients		n.s.	n.s.

Table 3.11: Magnesium concentration and root magnesium uptake over the four site years. Contrast statements include comparison of controls and the MOP at 189 kg K_2O ha^{-1} vs MOP with equivalent micronutrients of polyhalite at the same rate of K_2O

Treatment	Rate	Root Magnesium Concentration	Root Magnesium Uptake
	(kg K_2O ha^{-1})	(ppm)	(kg ha^{-1})
Control	0	1041 (66)	6.22 (0.4)
Control + Nitrogen (CN)	0	1037 (53)	6.53 (0.4)
Control + N & S (CNS)	0	1019 (59)	6.08 (0.6)
Polyhalite	31.5	1032 (43)	6.37 (0.4)
	63	951 (34)	6.56 (0.4)
	126	1017 (39)	7.93 (0.5)
	189	1033 (33)	7.15 (0.5)
Muriate of Potash	31.5	1038 (41)	7.06 (0.6)
	63	1003 (42)	7.00 (0.4)
	126	996 (52)	7.53 (0.6)
	189	942 (43)	6.77 (0.5)
MOP + nutrients	189	988 (46)	6.89 (0.5)
Effect		**Pr>F**	
Treatment		n.s.	n.s.
Contrasts			
Control vs CN		n.s.	n.s.
Control vs CNS		n.s.	n.s.
CN vs CNS		n.s.	n.s.
MOP vs MOP+nutrients		n.s.	n.s.

However, there were differences in sulfur concentration by treatment. Some polyhalite treatments, such as the 150% and 25% recommended K, resulted in larger sulfur concentrations in plant storage roots compared to the control and all MOP treatments with the exception of the MOP 150% recommended rate and MOP + micronutrient treatments (Table 12). The polyhalite 150% resulted in a sulfur concentration of 860 mg kg^{-1}, while the control only had a concentration of 746 mg kg^{-1} (Table 12).

Table 3.12: Sulfur concentration and root sulfur uptake over the four site years. Contrast statements include comparison of controls and the MOP at 189 kg K_2O ha^{-1} vs MOP with equivalent micronutrients of polyhalite at the same rate of K_2O.

Treatment	Rate	Root Sulfur Concentration	Root Sulfur Uptake
	(kg k_2o ha^{-1})	(mg kg^{-1})	(kg ha^{-1})
Control	0	746 (24) c	4.07 (0.5) c
Control + Nitrogen (CN)	0	818 (29) abc	4.84 (0.4) abc
Control + N & S (CNS)	0	815 (30) abc	4.36 (0.4) bc
Polyhalite	31.5	862 (30) a	4.89 (0.4) abc
	63	849 (27) ab	5.32 (0.4) abc
	126	819 (26) abc	5.99 (0.5) a
	189	860 (28) a	5.57 (0.5) ab
Muriate of Potash	31.5	763 (27) c	4.83 (0.5) abc
	63	775 (28) bc	5.05 (0.4) abc
	126	775 (29) bc	5.23 (0.4) abc
	189	789 (33) abc	5.20 (0.5) abc
MOP + nutrients	189	819 (26) abc	5.26 (0.6) abc
Statistics		**Pr>F**	
Treatment		<0.0001	0.0011
Contrasts			
Control vs CN		0.0023	n.s.
Control vs CNS		0.0034	n.s.
CN vs CNS		n.s.	n.s.

These findings can also be illustrated through a linear regression (Figure 9). There was a trend of sulfur stored in the root biomass increasing in concentration as polyhalite application rate increases. There are significant differences between three of the four polyhalite rates and the control.

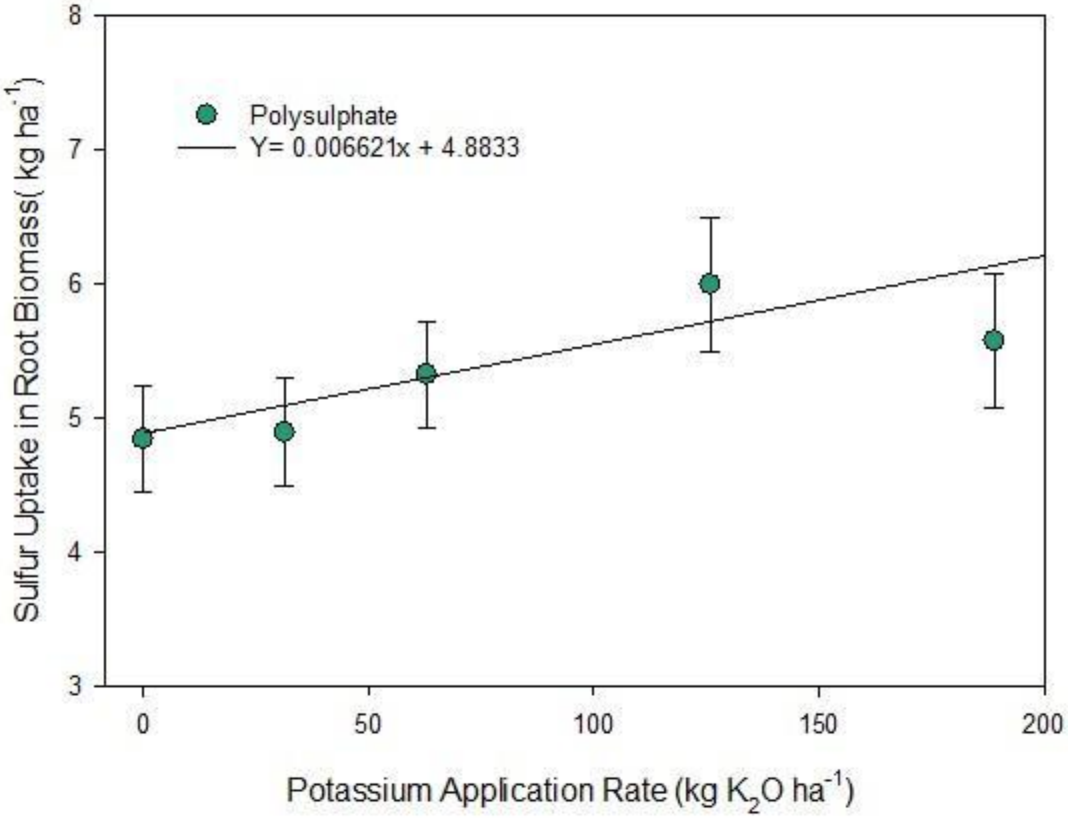

Figure 3.9: Linear regression of sulfur root biomass uptake over the four site years (2019, 2020, Goldsboro and Kinston). Polyhalite was analyzed as the only treatment receiving increasing rates of S fertilizer.

There were also significant differences between treatments in sulfur concentration in leaf tissue (Table 13). These findings are consistent with what is expected. S comprises 21.3% of the polyhalite mineral. The addition of polyhalite at any of the weights used in this study were sufficient enough to see adequate differences in S. This is due to the large quantities of S applied relative to the amount of soil S and plant required S. With higher rates of polyhalite applied, more S is likely to be available for plant uptake.

Although sweet potatoes in this study were able to take up and store more S, many nutrient studies that evaluate sulfur in sweet potatoes see no difference in yields, or difference in any other currently understood metric that is deemed useful for production. Other benefits to higher concentrations of sulfur in the sweet potato tissue, such as nutritional quality for human health, have not yet been studied. However, there are other crops that have been known to benefit in yield and quality with the addition of S. Such high concentrations of S contained in the polyhalite mineral may warrant the exploration of polyhalite as a fertilizer for a crop that requires high concentration of both potassium and sulfur. For example, onions (*Allium cepa*) are a crop that could benefit from such a fertilizer. A study that compared MOP, SOP, and polyhalite in onions found that polyhalite produced the best yields for onions (Ozkan et al., 2018). Ozkan et. al attributed this finding to the slow release properties of the polyhalite mineral to provide a sustained release of K and S. Future research may benefit from the exploration of this mineral fertilizer for high-value crops that require nutrients in ratios that are similar to what is contained in the polyhalite.

Conclusion

This study suggests that polyhalite can provide an adequate potassium supply for sweet potatoes. Polyhalite equates to MOP in terms of yields, and potassium storage. However, the proportion of jumbo sweet potatoes produced when polyhalite is used is greater than the control, unlike what is seen in the MOP treatments. The proportion of canners produced when polyhalite is used is less than the control, suggesting that polyhalite may influence the rate of maturity for sweet potatoes. This study also shows that sweet potatoes take up and store greater levels of sulfur when supplied with polyhalite compared to MOP and a control which received no additional sulfur. This suggests that polyhalite could potentially be advantageous to crops that require available sources of sulfur for production. The price and availability of agricultural fertilizers are unstable and rapidly changing. With a statistically similar yield response, the continued use of MOP as the primary K source is the most economical option. However, companies that mine this material are currently marketing that polyhalite is supplemented with a more pure form of potassium. This would allow the grower to benefit from the secondary and micronutrients within the mineral, while bringing down input costs if used with a product like MOP. Transportation costs for fertilizer distribution have increased sharply in recent times. These uncertainties are contributing to food insecurity. However, scientific advancements fueled by agricultural research are allowing mankind to keep up in a rapidly changing world.

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APPENDICES

Appendix A

Table 4.1: P Index manure application according to the North Carolina Phosphorus Loss Assessment Tool (PLAT).

Rating	P Index	Application
Low	0-25	Nitrogen based manure application is allowed
Medium	26-50	
High	51-100	P application should not exceed P removal of crop harvested
Very High	> 101	No additional P is allowed

Figure 4.1: Aerial Drone image of cover crop treatment plots. Cover crops can be seen at Kinston research station in 2021 prior to termination

Appendix B

Figure 4.2: Sweet potatoes were harvested 9/25/20 at CEFS location and 10/5/2020 at LCPRS. Data was collected from five feet by two rows for each plot

Table 4.2: Marketable yields and total root biomass over the four site years (2019, 2020, Goldsboro and Kinston).Contrast statements include comparison of controls and the MOP at 189 kg K2O ha-1 vs MOP with equivalent micronutrients of polyhalite at the same rate of K2O.

Treatment	Rate	Marketable Yields†	Total Root Biomass
	(kg K_2O ha^{-1})	(t ha^{-1})	(t ha^{-1})
Control	0	31.5 (2.6) ab	31.9 (2.6) ab
Control + Nitrogen (CN)	0	32.6 (2.3) ab	32.8 (2.3) ab
Control + N & Sulfur (CNS)	0	30.0 (2.3) b	30.2 (2.4) b
Polyhalite	31.5	31.7 (2.0) ab	31.9 (2.0) ab
	63	35.2 (2.3) ab	35.4 (2.3) ab
	126	39.5 (2.4) a	39.9 (2.3) a
	189	35.1 (2.7) ab	35.3 (2.7) ab
Muriate of Potash	31.5	34.3 (2.8) ab	34.4 (2.8) ab
	63	35.6 (1.7) ab	35.8 (1.7) ab
	126	37.1 (2.2) ab	39.0 (3.1) ab
	189	36.4 (2.4) ab	36.5 (2.4) ab
MOP + nutrients	189	35.3 (2.7) ab	36.1 (2.4) ab

Statistics	**Pr>F**

Table 3.2 (continued)

Treatment	0.0279	0.0142
Contrasts		
Control vs CN	n.s.	n.s.
Control vs CNS	n.s.	n.s.
CN vs CNS	n.s.	n.s.
MOP vs MOP+nutrients	n.s.	n.s.