NITROGEN FERTILIZATION STRATEGIES FOR SHORT-DAY ONION (*ALLIUM CEPA*) PRODUCTION IN GEORGIA

by

HANNA IBIAPINA DE JESUS

(Under the Direction of Timothy W. Coolong)

ABSTRACT

Georgia has an international reputation for producing short-day, sweet onions, commonly known as Vidalia onions. They are primarily cultivated in the southeastern region of the state, where the favorable climate and naturally low sulfur soils allow growers to produce onions with low pungency levels that garner high returns. Georgia farmers follow precise cultivation practices to ensure high-quality onions; nevertheless, significant challenges persist in optimizing nitrogen (N) fertilization of this crop. In the present dissertation, we conducted four studies that will help provide the information necessary to update N fertilizer recommendations for conventional and organic onions cultivated in Georgia. Results indicate that N fertilizer requirements for conventional onions will vary depending on rainfall levels but may be reduced from current recommendations. In years with high precipitation, N rates of 135 lb/acre N or more may be necessary to achieve sufficiently high yields of onions, while in drier years, as little as 75 lb/acre N may sustain commercially acceptable crop yields. Nitrogen fertilizer applications at the transplant stage are inefficient, with limited uptake by the onion plant. In contrast, N fertilizers applied during bulb initiation and bulb swelling stages are more efficiently used. Further, the final N application for the season should be carefully managed at bulb initiation to reduce the pungency levels of onions and maintain yields. For organic onions, increased organic fertilizer rates are shown to enhance total yield; however, a mixed-source organic (MIX) fertilizer was more effective than the more commonly used pelleted-poultry litter (PPL) fertilizer, as field studies indicates a reduced less N uptake efficiency by onions fertilized with PPL. Results from a lab-based incubation study using two common Georgia soils indicated that PPL fertilizer had 0% to 22% net N mineralization (Net N_{min}) after 120 days of incubation, whereas a MIX fertilizer had 26% to 59% Net Nmin, and a feather meal-based fertilizer provided 42% to 72% Net Nmin. Soil type and temperature had a lesser impact on N mineralization than fertilizer source. This suggested that the choice of organic fertilizer source is crucial for N availability during the cropping season.

INDEX WORDS: *Allium cepa*, *Burkholderia cepacian*, Feather meal, Mixed source organic fertilizer, Nitrogen uptake, Mineralization, Onion development stage, *Pantoea* spp., Pelleted poultry litter, Pungency, Vidalia

NITROGEN FERTILIZATION STRATEGIES FOR SHORT-DAY ONION PRODUCTION (*ALLIUM CEPA* L.) IN GEORGIA

by

HANNA IBIAPINA DE JESUS

BS, Federal Rural University of Amazonia, Brazil, 2017

MS, Federal University of Paraiba, Brazil, 2019

A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHYLOSOPHY

ATHENS, GEORGIA

2023

NITROGEN FERTILIZATION STRATEGIES FOR SHORT-DAY ONION PRODUCTION

(*ALLIUM CEPA* L.) IN GEORGIA

by

HANNA IBIAPINA DE JESUS

Major Professor: Timothy W. Coolong
Committee: Andre L. B. R. da Silva
Angelos Deltsidis
Bhabesh Dutta
Juan Carlos Diaz-Perez

Electronic Version Approved:

Ron Walcott
Vice Provost for Graduate Education and Dean of the Graduate School
The University of Georgia
December 2023

DEDICATION

To my son Noah, who has made me stronger and better than I could have ever imagined.

ACKNOWLEDGEMENTS

After four intense years I am finally reaching the end of my Ph.D. I would like to take this opportunity to express my gratitude to the many people who have played important roles in making this achievement possible.

First, my sincere thanks to my major advisor, Dr. Tim Coolong, for his support, guidance, and patience throughout this process. You have made this journey truly enjoyable, and I couldn't have asked for a better mentor.

I am also grateful to my committee members, Dr. Andre da Silva, Dr. Angelos Deltsidis, Dr. Bhabesh Dutta, and Dr. Juan Carlos Diaz-Perez, who have given me so much of their time. Thank you for all the support and feedback on my research.

Special thanks to Dr. Andre da Silva, who was my advisor when I started this journey and continued to provide support over the past four years – Your advice and good humor have been greatly appreciated. I thank Dr. Kate Cassity-Duffey, for helping me to develop part of my research and for always being there to talk, and for her patience during my learning process. I also thank the University of Georgia Horticulture Department faculty, graduate students, and staff for their support and help.

Next, I'd like to thank my family and friends. In special, my husband Jordao, who has given up so much to make my career a priority in our lives – I couldn't have done this without you. My son Noah, who is a blessing in my life. My parents, Marilene and Aecio, for the endless

love and support they have given me through my life. Lastly but not least, I thank God for letting me through all the challenges.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Onion (*Allium cepa* L.) is the most widely cultivated species from the genus *Allium* (Brewster, 2008). The onion, with its characteristic flavor, represents an important culinary ingredient around the world and a commodity with substantial economic value. China, India, and the United States (U.S.) are the world's top onion producers (FAO, 2018). In the U.S., onions rank as the fifth-largest crop in terms of acres planted, and Georgia claims a prominent position as the fifth-largest onion-producing state in the country (USDA, 2023).

Georgia has gained recognition for growing sweet, short-day onions, commonly known as Vidalia onions. They are primarily produced in the southeastern region of the state in portions of 20 counties that form a cultivation area outlined by Federal Marketing Order No. 955 (USDA, 1989). The production of Vidalia onions in Georgia started more than 80 years ago by a farmer named Moses Colemen. During that time, the industry has built a national reputation for the production of sweet and mild onions and Vidalia onions currently command premium prices in the national and international markets (Boyhan & Torrance, 2002).

The production of Vidalia onions in Georgia is facilitated by favorable climate conditions and soils that are naturally low in sulfur, which allow to produce onion with relatively low pungency levels (Boyhan & Torrance, 2002; Coolong & Boyhan, 2017). Additionally, farmers follow precise cultivation practices to ensure high yield and quality onion crops (Coolong & Boyhan, 2017). However, there remain significant challenges associated with optimizing nitrogen (N) fertilization of both conventional and organic short-day onions in Georgia.

The long growing season and shallow root system of onions necessitate that soil N must be consistently available throughout the production season to achieve optimal yields (Brewster, 2008; Halvorson et al. 2002). However, the sandy loam soils prevalent in southeastern Georgia increase the risk of N leaching, especially during periods of high rainfall (Boyhan & Torrance, 2002; Sharma et al. 2012). As a result, N fertilizer recommendations for growing short-day onions in Georgia are relatively high, ranging from 125 to 150 lb N/acre in conventional systems (Coolong & Boyhan, 2017). In organic onion systems, these N application rates tend to be even higher, normally exceeding the conventional rates by 50% to compensate for the uncertainty of N availability from organic fertilizers (Boyhan et al., 2007).

Excessive N fertilization of onions has been associated with low-quality onion bulbs; specifically, high soil N content at late-season has been found to negatively affect the flavor of onions and increase susceptibility to some diseases (Belo et al., 2023; Brewster, 2008; Coolong & Randle, 2003; Díaz-Pérez et al., 2003; Randle, 2000). Therefore, it is essential to establish an effective N fertilization program for onions cultivated in Georgia, striking a balance between providing the necessary N for optimal crop growth and yield while mitigating the adverse quality effects associated with excessive N fertilizer rates (da Silva et al., 2022; Geisseler et al., 2022)

Research Objectives

The main objective of these studies was to determine the N fertilizer application requirements for growing conventional and organic short-day onions in Georgia. The goal of this research was to develop the information necessary to establish N fertilizer recommendations for short-day onions cultivated in Georgia.

This dissertation comprised four studies which address the following research objectives:

1) Evaluate the effects of timing of the last N fertilizer application for the season in combination with three N fertilizer rates on the yield and quality of short-day onions.
2) Evaluate the FNUE of short-day onions across five developmental stages to optimize timing of fertilizer applications.
3) Compare the impact of a mixed source organic fertilizer and a pelleted poultry litter product applied at multiple application rates in two soil types on organic onion production.
4) Determine the potential N mineralization rates from three organic fertilizers commonly used for vegetable production in Georgia, USA, and to evaluate the effects of temperature on N mineralization from two of the most common agricultural soil types in Georgia over a 120-day period.

Literature Cited

Belo, T., du Toit, L. J., & LaHue, G. T. (2023). Reducing the risk of onion bacterial diseases: A review of cultural management strategies. *Agronomy Journal*, *115*(2), 459-473. https://doi.org/10.1002/agj2.21301

Boyhan, G. E., & Torrance, R. L. (2002). Vidalia Onions – Sweet Onion Production in Southeastern Georgia. *HortTechnology*. *12*(2), 196–202. https://doi.org/10.21273/HORTTECH.12.2.196

Boyhan, G. E., Torrance, R. L., & Hill, C. R. (2007). Effects of nitrogen, phosphorus, and potassium rates and fertilizer sources on yield and leaf nutrient status of short-day onions. *HortScience*, *42*(3), 653-660. https://doi.org/10.21273/HORTSCI.42.3.653

Brewster, J. L. (2008). Onions and other vegetable alliums (2nd edition). CABI, Wellesbourne, UK.

Coolong, T., & Boyhan, G. (2017). Onion production guide. *University of Georgia Cooperative Extension Bulletin* 1198.

Coolong, T. W., & Randle, W. M. (2003). Ammonium nitrate fertility levels influence flavour development in hydroponically grown 'Granex 33'onion. *Journal of the Science of Food and Agriculture*, *83*(5), 477-482. https://doi.org/10.1002/jsfa.1398 da Silva, A. L. B. R., Rodrigues, C., Dunn, L., Cavender, G., & Coolong, T. (2022). Fertilizer Nitrogen Application for Short-Day Onion Production: From Field to Table. *Horticulturae, 8*(9), 847. https://doi.org/10.3390/horticulturae8090847

Díaz-Pérez, J. C., Purvis, A. C., & Paulk, J. T. (2003). Bolting, yield, and bulb decay of sweet onion as affected by nitrogen fertilization. *Journal of the American Society for Horticultural Science, 128*(1), 144-149. https://doi.org/10.21273/JASHS.128.1.0144

Food and Agriculture Organization of the United Nations. (2018). World onion production. Food and Agriculture Organization of the United Nations. http://faostat.fao.org (accessed 14 sept 2023)

Geisseler, D., Ortiz, R. S., & Diaz, J. (2022). Nitrogen nutrition and fertilization of onions (Allium cepa L.)–A literature review. *Scientia Horticulturae, 291*. https://doi.org/10.1016/j.scienta.2021.110591

Halvorson, A. D., Follett, R. F., Bartolo, M. E., & Schweissing, F. C. (2002). Nitrogen fertilizer use efficiency of furrow-irrigated onion and corn. *Agronomy Journal, 94*(3), 442-449. https://doi.org/10.2134/agronj2002.4420

Randle, W. M. (2000). Increasing nitrogen concentration in hydroponic solutions affects onion flavor and bulb quality. *Journal of the American Society for Horticultural Science, 125*(2), 254-259. https://doi.org/10.21273/JASHS.125.2.254

Sharma, P., Shukla, M. K., Sammis, T. W., & Adhikari, P. (2012). Nitrate-nitrogen leaching from onion bed under furrow and drip irrigation systems. *Applied and Environmental Soil Science, 2012*, 1-17. https://doi.org/10.1155/2012/650206

US Department of Agriculture, National Agricultural. (2023). Vegetables 2022 Summary (February 2023). https://usda.library.cornell.edu/concern/publications/02870v86p?locale=en

US Department of Agriculture. (1989). Marketing order: Vidalia onions grown in Georgia. Code Fed. Regulat., Chapter IX, Part 955. USDA, Wash., D.C.

CHAPTER 2

LITERATURE REVIEW

The History and Economical Importance of Onion

Onion (*Allium cepa* L.) is one of the most important species from the *Allium* genus that also includes garlic (*Allium sativum* L.), chives, shallots, and leeks. They are believed to be one of the earliest cultivated crops, and although the history of ancestral onion species is not well documented, their center of origin is believed to be from central Asia and the Mediterranean regions. The exact location of onion domestication is still a subject of debate, but historical evidence suggests the presence of onion in these regions for at least 5000 years (Astley et al., 1982; Brewster, 1994).

Over time, the versatility and adaptability of onion favored its widespread cultivation worldwide, making it an essential ingredient in many culinary traditions. It is not only a vegetable consumed raw, but also serves as a key ingredient in numerous culinary preparations, enhancing the flavor of dishes worldwide (Randle, 1997). Furthermore, onions are known for their antioxidant and anti-inflammatory properties due to the presence of compounds such as flavonoids, anthocyanins, fructo-oligosaccharides, and organosulphur compounds, making it a versatile vegetable with economic significance (Griffiths et al., 2002; Goldman, 2011).

Onion is ranked as the second most economically significant vegetable crop worldwide (FAO, 2022). Onions have been extensively bred for adaptation to various regions around the world. About 170 countries are known to cultivate onions, and approximately 6 million acres are harvested every year on a global scale. The primary onion-growing countries, China and India, play an important role in global production, followed by the USA, Egypt, Iran, Pakistan, and Turkey (FAO, 2018). These countries collectively contribute to the vast availability of onions in the market, with varieties of different colors, shapes, and flavors ranging from sweet to pungent. In the U.S., about 127,000 acres of onion are annually grown making onion the third largest crop grown in the country, with more than 6.7 billion pounds of onions harvested annually (USDA, 2023).

The Onion Plant

Onion plants feature a flattened stem below ground, forming a disc-shaped base. At the center of this stem disc emerge their leaves, alternately and oppositely, resulting in two ranks of leaves at 180-degree angles. Onion leaves are hollow with longitudinal symmetry, consisting of a blade and a sheath that encircle the growing point. Interestingly, what initially appears as the stem is a *pseudostem* formed by concentric leaf sheaths (DeMason, 1990). As new leaves grow near the shoot apex, older sheath bases are gradually pushed away from it due to lateral expansion. Roots develop near the base of young leaves and extend downward (DeMason, 1990). The stem remains compressed unless flowering occurs, at which point it transforms into an inflorescence. Onions must undergo a period of vernalization to flower, which requires a period of cold temperatures, typically around 32-50°F (0-10°C), during their initial growth stage (Brewster, 1990). However, before flower induction, onions must have reached a minimum stage of maturity for flowering to be initiated. If cold temperatures are present prior to this stage flowering may not occur (Brewster, 1990)

The onion bulb is the first organ of interest of the crop. It is an aggregate of swollen leaf bases and the vegetative stem axis, formed from the mobilization of carbohydrates into the base of young leaves. When bulb formation is induced, the foliage leaves progressively change from a photosynthetic activity to a storage activity, in which the leaf laminae become reduced, while the sheath becomes fleshy structures often described as scale leaves (Heath & Holdsworth, 1948). An important aspect of onion bulb development is the photoperiod (or day length), which determines when bulb development begins. However, other factors such as temperature, light intensity and quality, plant nutrition and water availability can influence bulb growth somewhat (Brewster, 1990; Kato, 1964).

Onion is a biennial plant by nature, but it is usually grown as an annual. Considered a cool-season crop, onions have been adapted to most regions of the world through selection for bulb responses to photoperiod (Boyhan & Torrance, 2002). They can be broadly categorized into short, intermediate, and long days varieties requiring a minimum of 11, 13 and 14 hours of day length, respectively, induce bulbing. As a result, cultivar selections for different regions are often based on photoperiod requirements (Brewster, 2008). Onions grown in the Vidalia region are all short-day types due to the minimum daylength in the area in early spring. While intermediate-day onions could be grown in the region, they would not bulb until late spring or early summer at which point temperatures in the region would not be conducive to production. In addition to photoperiod classification, onions are also categorized by flesh color (red, white, brown, or yellow), taste (sweet or pungent), and shape of the bulb (round, flat, or globe), final use (dehydrated and processed or fresh consumption), and whether they are utilized quickly after harvest or stored for extended periods of time (Harrison et al., 2008). These various classifications offer a wide range of onion options to suit diverse culinary preferences and growing conditions. According to the federal marketing order for Vidalia onions, they must be a yellow, short-day, Granex (shape) type onion to be sold as a Vidalia onion (USDA, 1989).

The Chemistry of Onion Flavor

The characteristic flavor of onions is primarily attributed to the presence of organosulfur compounds, in particular S-alk(en)yl cysteine sulfoxides (ACSOs) (Lancaster & Boland, 1990). There are three major ACSOs that are found in onions: S-1-propenyl cysteine sulfoxide (PRENCSO), often found in the highest concentration in pungent onions, S-methyl-cysteine sulfoxide (MCSO) found in in lesser amounts, and S-propyl-cysteine sulfoxide (PCSO), which is often present in the lowest concentrations (Boelens et al., 1971; Lancaster et al., 1998). The combinations of these ACSOs help give onions their unique flavors. While pungent onions typically have a preponderance of PRENCSO, mild onions such as those grown in Vidalia, GA, USA may present a greater proportion of MCSO relative to other ACSOs (Coolong & Randle, 2003). The formation of ACSOs in onion begins with the uptake of sulfur in the form of sulfate (SO_4^{-2}). Sulfur is subsequently assimilated into various sulfur-containing amino acids. One specific amino acid, cysteine, follows the path through the glutathione cycle to be incorporated into γ-glutamyl peptides (γ-GPs). These peptides act as intermediates in the pathway that ultimately results in the accumulation of ACSOs within onion bulbs (Block, 1992; Lancaster & Boland, 1990; Lancaster et al., 1998).

When onion tissue is mechanically disrupted and vacuoles are lysed, the enzyme alliinase hydrolyses the ACSOs presented within the cells, which gives rise to a range of volatile compounds, such as propanethial S-oxide, the lachrymatory factor of onions, and other molecules that contributes to the unique flavors and aromas associated with onions (Yoo et al., 2012). Pyruvic acid, which is a stable bi-product of these reactions is often used as an indicator of onion pungency. Pyruvic acid is relatively easy to measure using colorimetric methods and although, it does not contribute to flavor directly it has been well correlated to the presence of flavor compounds, is used widely as an indicator of the flavor precursor content and is a well-established method for accessing onion pungency (Schwimmer & Weston, 1961; Tekalign et al., 2012).

In addition to sulfur compounds, sweetness plays a vital role in onion flavor, with sugars like glucose, sucrose, and fructose comprising most soluble solids (Breu, 1996; Vavrina and Smittle, 1993). The sugar-to-pungency ratio ultimately determines the overall onion flavor, but the precise contribution of sugars can be challenging to discern, especially in pungent or uncooked onions, where other flavor compounds may mask sweetness (Kim et al., 2017; Vavrina & Smittle, 1993). The taste of Vidalia onions is perceived to be sweeter than many other types of onions, but this is not necessarily the result of having more sugars present. Instead, it is the lack of pungent sulfur compounds that allow the sugars to be perceived by the consumer, giving Vidalia onions their sweet flavor (T. Coolong, personal communication).

The Production of Short-Day Onion in Georgia, USA

Georgia holds a prominent position in U.S. onion production, standing as the fifth-largest onion-producing state in the country. The farm gate value of onion in Georgia exceeds $168 million, which places it as the third most valuable vegetable crop in the state, behind sweet corn and watermelon (University of Georgia, 2022). Georgia has gained a reputation for growing short-day onions, commonly known as Vidalia onions.

Vidalia onions are yellow Granex-type onions cultivated in Georgia for over 80 years. The production of Vidalia onions is centered in the southeastern region of the state, where 20 counties participate in a designated cultivation area outlined by the Federal Marketing Order No. 955 (USDA, 1989). The success of Georgia’s onion production is attributed to the unique climate and soil conditions found in the southeastern region of the state, where the mild winters and well-drained, sandy soils create an ideal environment for short-day onion cultivation (Boyhan &

Torrance, 2002). These soils, notably low in sulfur content, offer growers greater flexibility in managing sulfur levels to produce sweet onions. This, combined with the careful selection of low pungency onion varieties, contributes to the sweet and mild taste of Vidalia onions, for which they have gained a reputation in national and international onion markets (Boyhan & Torrance, 2002; Olsson, 2012).

Georgia farmers follow precise cultivation practices, to ensure the high quality and distinctive sweet flavor of Vidalia onions. Transplanting typically is done throughout November, though can occur as early as October and as late as early January. During this time daylight hours gradually decrease but mild temperatures still allow for good leaf development. As winter progresses and days become shorter, growth slows. Onions enter the bulb initiation phase in February as daylength reaches 11 hours or more. The growing season continues until spring, when daily air temperatures rise sufficiently to promote bulb enlargement, forming the characteristic large bulbs that are desired. Harvesting typically occurs in late spring (April and May) (Boyhan & Torrance, 2002; Coolong & Boyhan, 2017).

Nitrogen Fertilization of Onion in Georgia, USA

Nitrogen (N) is an essential nutrient for plants, as it plays a vital role in the synthesis of amino acids, proteins, and chlorophyll (Parry et al., 2003; Taiz & Zeiger, 2006). Onions have relatively high N requirements; therefore, the successful production of onions relies on implementing the N fertilizer program that efficiently meets the crop's nutritional needs and maximizes yield and bulb quality (Brewster, 2008).

Onions have a relatively shallow root system, most active roots concentrated within the upper 15 cm of soil, with their maximum rooting depth typically reaching 30 cm (Ajdary et al., 2007; Machado et al., 2009; Strydom, 1964). This characteristic can mean that onions are relatively poor competitors for water and nutrients from the soil. For onions cultivated in the Coastal Plain region of southeastern Georgia, USA, where sandy loam soils predominate, there is an increased risk of N leaching and less utilization of N fertilizer by the plant (Boyhan & Kelley, 2008; Delgado, 2002). In addition to a shallow root system, onions are planted at a relatively high density per unit area, which suggests that significant N is required to support a relatively large amount of above-ground biomass per unit area (H.I. De Jesus, unpublished data).

Crop N recommendations vary widely depending on factors such as soil type, rainfall, irrigation, plant populations and method and timing of application. Existing literature on N fertilization of short-day onions in the southeast of Georgia recommends applying about 125 to 150 lb/acre N throughout the season (Coolong & Boyhan, 2017). This typically involves incorporating 25% to 30% of total N prior to planting, with the remainder split into three or more applications; with the final application at least 4 weeks prior to harvest. (Coolong & Boyhan, 2017).

Despite the well-established fertilizer program for onions in Georgia, USA, much of the field research supporting these N levels dates back to more than two decades (Batal et al., 1994; Boyhan et al., 2007; Díaz-Pérez et al., 2003; Randle, 2000). Recently growers have shifted nutrient management practices, successfully producing high-quality crops with less N fertilizer inputs by splitting the N fertilizer rate into four or more applications throughout the season (C. Tyson, personal communication). Many growers in the region apply their first N application at or shortly after at transplanting, followed by a second application during the early vegetative growth stage to promote root and leaf growth; the remaining N is typically divided into two additional applications in the latter half of the season. This helps to avoid excessive levels of N fertilizer around the root zone and minimizes the risk of nitrogen loss through leaching (da Silva et al., 2022; Geisseler et al., 2022).

Recent studies have suggested that commercially acceptable yields can be achieved with as little as 105 lb/acre N split into four applications throughout the season (da Silva et al., 2022). However, it is crucial to fine-tune the timing of fertilizer applications to align with key developmental stages of the onion plant. This strategic approach can significantly reduce the total nitrogen requirement, ultimately enhancing crop fertilizer nitrogen use efficiency (FNUE) (Geissler et al., 2022). Further research on N fertilization strategies holds promise for the implementation of an updated nitrogen fertilizer program tailored specifically for short-day onions in Georgia.

The Organic Onion Production in Georgia, USA

Organic vegetable production has steadily increased in the US for the past decade (Organic Trade Association, 2023). In Georgia organic Vidalia onions are the single most valuable organic vegetable produced with more than 793 acres, representing roughly 7% of the total acreage dedicated to Vidalia onion production, in 2019 according to the US Department of Agriculture (USDA, 2019). This represents a value of at least $12 million, which continues to increase annually. Although organic production can be lucrative for Vidalia onion growers, there is a need to reduce significant input costs. Onion growers devote a considerable amount of resources for organic fertilizers. There is significant variability of N release among organic fertilizers since most nutrients are tied up in organic forms and N mineralization is necessary for plant N uptake (Dorais & Alsanius, 2015). The release of mineral N from organic fertilizers varies depending on factors like the source material, soil characteristics, and environmental conditions (Calderón et al. 2005; Cassity-Duffey et al. 2018; Reganold & Wachter 2016); as a result, the plant N availability is hard to predict, and failing to synchronize the timing between N release and onion N requirements can significantly reduce yields of onion crops (Berry et al., 2002).

Organic fertilizers are typically applied to onions in Georgia at rates at least 50 percent higher than conventional N-P-K percentages to compensate for the uncertainty surrounding N availability (Boyhan et al., 2007). Although fresh, non-composted poultry litter (PL) is readily available, growers may be reluctant to rely on it as a primary source of fertilizer due to food safety concerns (R. Hamlin, personal communication). Therefore, growers may rely on pasteurized or pelleted poultry litter (PPL) products or commercial organic fertilizers from mixed sources. For those that still use PL, it may only contain 2% to 4% total N, with limited availability during the cropping season (Chastain et al. 2001; Evers 1998). Commercial organic fertilizers, typically made from plant or animal byproducts, are available for certified organic vegetable production. These products can vary widely in N concentration, ranging from 3% to 15%, but in general, they offer more consistent N mineralization rates compared to PL and composts (Agehara & Warncke 2005; Cassity-Duffey et al. 2020; Gale et al. 2006; Hartz & Johnstone 2006).

Nitrogen Fertilization and Bulb Quality Parameters

Continuous availability of soil N may result in higher yields of onions, but the balance and the correct management of fertilizer is important to reduce offsite movement of N as well as ensure bulb quality. For Vidalia onions, flavor is one of the most important quality attributes affected by N fertilization. Because of the interactions between sulfur and N assimilation in plants, excessive N fertilization of onions, particularly at the end of the growing season, may increase pungency by promoting the accumulation of sulfur containing ACSOs within the bulbs (Coolong & Randle, 2003; Randle, 2000).

Studies on the flavor of onions underscore the significant influence of soil N availability on bulb ACSO concentrations. Randle (2000) reported that increasing N fertilization rates resulted in higher concentrations of MCSO, in hydroponically grown onions. Sometimes high levels of MCSO can impart cabbage-like flavors to onions (Block, 1992). Similarly, Coolong & Randle (2003) observed a nearly 250% increase in MCSO concentration in bulbs as N levels increased.

In addition to flavor, N availability can affect the susceptibility of onion plants to pests and diseases. Generally, when N fertilizer rates fall below the plant's requirements, it results in weaker plants that are more susceptible to attacks from pests and diseases (Brewster, 2008). However, while appropriate N nutrition can enhance growth and overall plant health, several studies indicate that excessive N applications can also be linked to higher disease rates (Awad et al., 1978; Batal, et al., 1994; Belo et al., 2023). As soil N availability increases, plants tend to exhibit luxury N consumption, leading to onion bulbs and leaves becoming more succulent, which in turn makes them more susceptible to pathogen attacks; furthermore, late N fertilizer application is likely to delay bulb maturation, thus extending the window for infection of several pathogens (Belo et al., 2023).

In a previous study, Díaz-Perez et al. (2003) reported that the percentage of decayed bulbs due to bacterial infection increased linearly with both N applied and N bulb content, in which 53% of bulbs had the disease at 175 lb./ac of N-fertilizer. According to authors, disease incidence had critical impact on the marketable yield of short-day onions. In another study, Tekalign et al. (2012) found that rotting of bulbs was significantly influenced by N rate, with the highest incidence at the rates of 102 and 123 lb. of N/ac.

Impact of Nitrogen Fertilization in Onion Storage

Storage is a critical aspect of managing short-day onions in Georgia as it extends their availability throughout the year while maintaining market standards, which is important given the premium prices often associated with Vidalia onions. The appearance of onion bulbs in terms of skin color, bulb firmness and the absence of damage during and after storage are important aspects that will determine marketability and consumer acceptance (Petropoulos et al., 2017).

The quality of onion bulbs during storage can be influenced by pre-harvest conditions, such as cultivation practices and the developmental stage at harvest, in addition to the implementation of various post-harvest procedures such as bulb handling, curing, storage conditions and treatments (Coolong & Boyhan, 2017). These factors collectively can have a direct impact on the main features during storage and, consequently, determine the quality of onion bulbs in the long term (Petropoulos et al., 2017).

The influence of excessive N fertilization in onion quality can be intensified by the various physiological and biochemical changes that occur within onion bulbs during storage, including water content, and the concentration of flavor compounds that increase the pungency of onions over time (Brewster, 2008; Sharma et al., 2014). Additionally, many symptoms from pathogen infection established during the growing season will only be visible during storage, where conditions can favor pathogen growth and activity, resulting in visible symptoms of rot or decay (Dutta & Gitaitis, 2020); the role of N fertilization in this context is particularly important, as excessive N can lead to delayed bulb maturation and predispose onions to pathogen infection late in the season. Bulbs that are harvest prior to full maturity are prone to disruptions in curing, all of which render onions more susceptible to post-harvest diseases (Petropoulos et al., 2017).

Major Onion Bacterial Diseases in Georgia, USA

Center rot (*Pantoea* spp.*)* in onions is a significant bacterial disease of economic concern in Georgia, caused by bacteria species within the *Pantoea* complex (Dutta et al., 2014). The initial identification of center rot in Georgia-grown onions dates to 1997, when *Pantoea ananatis* was linked to the infection of Vidalia onions (Gitaitis & Gay, 1997). Since then, other closely related *Pantoea* species have been identified as causal agents of center rot, including *Pantoea agglomerans*, *Pantoea allii* and *Pantoea stewartii* subs. *indologenes* (Brady et al., 2011; Edens et al., 2006; Stumpf et al., 2018). The causative agents of center rot exhibit a complex life cycle, characterized by various mechanisms of survival and dissemination. They can be seedborne and utilize infested onion seeds as a means of both survival and transmission, as well as over-season on several weed species (Agarwal et al., 2019). Additionally, a distinctive feature of species within the *Pantoea* complex is their transmission by tobacco (*Frankiella fusca*) and onion (*Thrips tabaci*) thrips (Dutta et al., 2014; Gitaitis et al., 2003).

Symptoms of center rot manifest on both the foliage and bulbs of onions as the pathogen moves from the infected leaves to bulb scales (Carr et al., 2013). On the leaves, the symptoms appear as water-soaked lesions along the length of the leaf, progressively turning necrotic. In the bulbs the internal tissues exhibit discoloration. In addition, bulbs may be predisposed to secondary infections, which might result in the liquification of bulb tissue (Carr et al., 2013; Dutta et al., 2014; Gitaitis et al., 2002; Stumpf et al., 2017). Center rot typically occurs during the later stages of bulb development and storage, leading to significant post-harvest losses (Stumpf et al., 2017; Walcott et al. 2002). With favorable conditions, such as a hot and humid growing season, growers can experience yield losses of up to 100% caused by center rot (Walcott et al. 2002).

Sour skin is another relevant bacterial disease of onions in Georgia, primarily caused by the soil-borne bacterium *Burkholderia cepacia* (Burkholder, 1950). Infection typically occurs through wounds (including those during harvest when onion tops are cut), other mechanical injuries around the neck area, rain-splashing of infested soil, or contaminated irrigation water (Burkholder, 1950; Davis, 2008). Symptoms of sour skin appear as the rotting of onion bulbs, which can be brown to reddish brown in color, and a prominent vinegar odor, from which the disease earned its name (Burkholder, 1950; Davis, 2008). Sour skin is particularly problematic during warm and humid conditions, which typically occur late in the onion production season in southern Georgia. The disease is one of the most important post-harvest pathogens associated with onions, and yield losses from sour skin can be as high as 50% annually (Burkholder, 1950; Davis, 2008).

Effective control measures are critical to preserving the quality and marketability of Georgia's onion crops, as several bacterial diseases, including center rot and sour skin, pose significant threats to onion. Management strategies involve implementing strict sanitation practices, such as utilizing disease-resistant onion cultivars when available, practicing careful sanitation to minimize spread through contaminated planting material and equipment, optimizing water management to reduce moisture, and using bactericidal treatments as necessary. Growers also routinely apply copper-based bactericides as a prophylactic measure to protect against bacterial disease in onion. Furthermore, continuous research and extension efforts are crucial in refining and disseminating these management strategies to onion growers, helping to maintain the health and productivity of onion crops in Georgia (Dutta & Gitaitis, 2020).

Literature Cited

Agarwal, G., Stumpf, S., Kvitko, B., & Dutta, B. (2019). Center Rot of Onion. *The Plant Health Instructor.* DOI: 10.1094/PHI-I-2019-0603-01

Agehara, S., & Warncke, D. D. (2005). Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. *Soil Science Society of America Journal, 69*(6), 1844-1855. https://doi.org/10.2136/sssaj2004.0361

Ajdary, K., Singh, D. K., Singh, A. K., & Khanna, M. (2007). Modelling of nitrogen leaching from experimental onion field under drip fertigation. *Agricultural water management, 89*(1-2), 15-28. https://doi.org/10.1016/j.agwat.2006.12.014

Astley D., Innes N. L., & Van Der Meer Q. P. (1982). Genetic resources of Allium species: A global report. *International Board for Plant Genetic Resources, 4,*2621.

Awad, M. A., El-Shenawy, Z., Omran, A. F., & Shatla, M. N. (1978). Cultural practices in relation to purple blotch disease of onion. *Scientia Horticulturae*, *9*(3), 237-243. https://doi.org/10.1016/0304-4238(78)90005-5

Batal, K. M., Bondari, K., Granberry, D. M., & Mullinix, B. G. (1994). Effects of source, rate, and frequency of N application on yield, marketable grades and rot incidence of sweet onion (Allium cepa L. cv. Granex-33). *Journal of Horticultural Science, 69*(6), 1043-1051. https://doi.org/10.1080/00221589.1994.11516543

Belo, T., du Toit, L. J., & LaHue, G. T. (2023). Reducing the risk of onion bacterial diseases: A review of cultural management strategies. *Agronomy Journal*, *115*(2), 459-473. https://doi.org/10.1002/agj2.21301

Berry, P. M., Sylvester-Bradley, R., Philipps, L., Hatch, D. J., Cuttle, S. P., Rayns, F. W., & Gosling, P. (2002). Is the productivity of organic farms restricted by the supply of available nitrogen?. *Soil Use and Management, 18,* 248-255. https://doi.org/10.1111/j.1475-2743.2002.tb00266.x

Block, E. (1992). The organosulfur chemistry of the genus Allium–implications for the organic chemistry of sulfur. *Angewandte Chemie International Edition in English*, *31*(9), 1135-1178. https://doi.org/10.1002/anie.199211351

Boelens, M., De Valois, P. J., Wobben, H. J., & Van der Gen, A. (1971). Volatile flavor compounds from onion. *Journal of Agricultural and Food Chemistry, 19*(5), 984-991.

Boyhan, G. E., Torrance, R. L., & Hill, C. R. (2007). Effects of nitrogen, phosphorus, and potassium rates and fertilizer sources on yield and leaf nutrient status of short-day onions. *HortScience*. *42*(3):653–660. https://doi.org/10.21273/HORTSCI.42.3.653.

Boyhan, G. E., & Torrance, R. L. (2002). Vidalia Onions – Sweet Onion Production in Southeastern Georgia. *HortTechnology*. *12*(2), 196–202. https://doi.org/10.21273/HORTTECH.12.2.196

Brady, C. L., Goszczynska, T., Venter, S. N., Cleenwerck, I., Vos, P., Gitaitis, R. D., Coutinho, T. A., and de Vos, P. (2011). Pantoea allii sp. nov., isolated from onion plants and seed. Int. J. Syst. Evol. Microbiol. 61:932-937. https://doi.org/10.1099/ijs.0.022921-0

Breu, W. (1996). Allium cepa L.(onion) Part 1: Chemistry and analysis. *Phytomedicine*, *3*(3), 293-306.

Brewster, J.L. (1994). Onions and other vegetable alliums. CAB Intl., Wallingford, UK.

Brewster, J. L. (1990). Physiology of crop growth and bulbing. In: Rabinowitch, H. D., & Brewster, J. L. (eds.). *Onions and allied crops* (pp. 53-88). CRC press.

Brewster, JL. 2008. Onions and other vegetable alliums (2nd edition). CABI. Wellesbourne, UK.

Burkholder, W. H. (1950). Sour skin, a bacterial rot of onion bulbs. *Phytopathology, 40*(1), 115-117.

Cabrera, M. L., Kissel, D. E., & Vigil, M. F. (2005). Nitrogen mineralization from organic residues: Research opportunities. *Journal of environmental quality, 34*(1), 75-79. https://doi.org/10.2136/sssaj2004.0361

Calderón, F. J., McCarty, G. W., & Reeves, J. B. (2005). Analysis of manure and soil nitrogen mineralization during incubation. Biol Fert Soils. 41:328-336. https://doi.org/10.1007/s00374-005-0843-x

Calderón, F. J., McCarty, G. W., & Reeves, J. B. (2005). Analysis of manure and soil nitrogen mineralization during incubation. *Biology and Fertility of soils, 41*, 328-336. https://doi.org/10.1007/s00374-005-0843-x

Cassity-Duffey, K., Cabrera, M., Gaskin, J., Franklin, D., Kissel, D., & Saha, U. (2020). Nitrogen mineralization from organic materials and fertilizers: Predicting N release. *Soil Science Society of America Journal*, *84*(2), 522-533. https://doi.org/10.1002/saj2.20037

Cassity-Duffey, K. B., Moore, A., Satterwhite, M., & Leytem, A. (2018). Nitrogen mineralization as affected by temperature in calcareous soils receiving repeated applications of dairy manure. *Soil Science Society of America Journal*, *82*(1), 235-242. https://doi.org/10.2136/sssaj2017.02.0044

Chastain, J. P., Camberato, J. J., & Skewes, P. (2001). Poultry manure production and nutrient content. In: *Confined animal manure managers certification program manual: Poultry version.* https://www.clemson.edu/extension/camm/manuals/poultry/pch3b_00.pdf (accessed 25 Feb 2023).

Coolong, T., & Boyhan, G. (2017). Onion production guide. *University of Georgia Cooperative Extension Bulletin* 1198.

Coolong, T. W., & Randle, W. M. (2003). Ammonium nitrate fertility levels influence flavour development in hydroponically grown 'Granex 33'onion. *Journal of the Science of Food and Agriculture*, *83*(5), 477-482. https://doi.org/10.1002/jsfa.1398

Davis, R.M. 2008. Sour skin. (2007). In: Schwartz, H. F., & Mohan, S. K. (eds.). *Compendium of onion and garlic diseases and pests* (2nd edition, pp. 63-64). APS Press. St. Paul, MN.

da Silva, A. L. B. R., Rodrigues, C., Dunn, L., Cavender, G., & Coolong, T. (2022). Fertilizer Nitrogen Application for Short-Day Onion Production: From Field to Table. *Horticulturae*, *8*(9), 847. https://doi.org/10.3390/horticulturae8090847

Delgado, J. A. (2002). Quantifying the loss mechanisms of nitrogen. *Journal of Soil and Water Conservation*, *57*(6), 389-398.

DeMason, D. A. (1990). Morphology and anatomy of Allium. In: Rabinowitch, H. D., & Brewster, J. L. (eds.). *Onions and allied crops* (pp. 27-51). CRC press.

Díaz-Pérez, J. C., Purvis, A. C., & Paulk, J. T. (2003). Bolting, yield, and bulb decay of sweet onion as affected by nitrogen fertilization. *Journal of the American Society for Horticultural Science*, *128*(1), 144-149. https://doi.org/10.21273/JASHS.128.1.0144

Dorais, M., & Alsanius, B. (2015). Advances and trends in organic fruit and vegetable farming research. *Horticultural reviews*, *43*, 185-268. https://doi.org/10.1002/9781119107781.ch04

Drost, D., Koenig, R., & Tindall, T. (2002). Nitrogen use efficiency and onion yield increased with a polymer-coated nitrogen source. *HortScience*, *37*(2), 338-342. https://doi.org/10.21273/HORTSCI.37.2.338

Dutta, B., & Gitaitis, R. (2020). Bacterial Diseases of Onions in Georgia. *University of Georgia Cooperative Extension Bulletin 1534.*

Dutta, B., Barman, A. K., Srinivasan, R., Avci, U. T. K. U., Ullman, D. E., Langston, D. B., & Gitaitis, R. D. (2014). Transmission of Pantoea ananatis and P. agglomerans, causal agents of center rot of onion (Allium cepa), by onion thrips (Thrips tabaci) through feces. *Phytopathology*, *104*(8), 812-819. https://doi.org/10.1094/PHYTO-07-13-0199-R

Edens, D. G., Gitaitis, R. D., Sanders, F. H., & Nischwitz, C. (2006). First report of Pantoea agglomerans causing a leaf blight and bulb rot of onions in Georgia. *Plant Disease*, *90*(12), 1551-1551. https://doi.org/10.1094/PD-90-1551A

Evers, G. W. (1998). Comparison of broiler poultry litter and commercial fertilizer for coastal bermudagrass production in the southeastern US. *Journal of Sustainable Agriculture*, *12*(4), 55-77. https://doi.org/10.1300/J064v12n04_06

Food and Agriculture Organization of the United Nations. (2018). World onion production. Food and Agriculture Organization of the United Nations. http://faostat.fao.org (accessed 14 sept 2023)

Food and Agriculture Organization of the United Nations. (2022). Agricultural production statistics. 2000–2020. FAOSTAT Analytical Brief Series No. 41. Rome. http://faostat.fao.org (accessed 14 sept 2023)

Gale, E. S., Sullivan, D. M., Cogger, C. G., Bary, A. I., Hemphill, D. D., & Myhre, E. A. (2006). Estimating plant-available nitrogen release from manures, composts, and specialty products. *Journal of Environmental Quality*, *35*(6), 2321-2332. https://doi.org/10.2134/jeq2006.0062

Gitaitis, R., Walcott, R., Culpepper, S., Sanders, H., Zolobowska, L., & Langston, D. (2002). Recovery of Pantoea ananatis, causal agent of center rot of onion, from weeds and crops in Georgia, USA. *Crop Protection, 21*(10), 983-989. https://doi.org/10.1016/S0261-2194(02)00078-9

Gitaitis, R. D., Walcott, R. R., Wells, M. L., Perez, J. D., & Sanders, F. H. (2003). Transmission of Pantoea ananatis, causal agent of center rot of onion, by tobacco thrips, Frankliniella fusca. *Plant Disease, 87*(6), 675-678. https://doi.org/10.1094/PDIS.2003.87.6.675

Griffiths, G., Trueman, L., Crowther, T., Thomas, B., & Smith, B. (2002). Onions—a global benefit to health. *Phytotherapy Research: An International Journal Devoted to Pharmacological and Toxicological Evaluation of Natural Product Derivatives*, *16*(7), 603-615.

Goldman, I. L., & Havey, M. J. (1998). History and pedigree of public onion releases in the United States. In Voss, R. (Ed.), *Proc. 1998 Natl. Onion (and Other Allium) Res. Conf*, (pp. 25-34). Sacramento, CA.

Geisseler, D., Ortiz, R. S., & Diaz, J. (2022). Nitrogen nutrition and fertilization of onions (Allium cepa L.)–A literature review. *Scientia Horticulturae*, *291*. https://doi.org/10.1016/j.scienta.2021.110591

Gitaitis, R. D., & Gay, J. D. (1997). First report of a leaf blight, seed stalk rot, and bulb decay of onion by Pantoea ananas in Georgia. *Plant disease*, *81*(9), 1096-1096. https://doi.org/10.1094/PDIS.1997.81.9.1096C

Gonçalves, F. A. R., de Aquino, P. M., Duarte, L. O., de Aquino, R. F. B. A., dos Reis, M. R., & de Aquino, L. A. (2019). Curvas de extração de macronutrientes pela cultura da cebola. *Semina: Ciências Agrárias*, *40*(6), 2497-2512. https://doi.org/10.5433/1679-0359.2019v40n6p2497

Griffiths, G., Trueman, L., Crowther, T., Thomas, B., & Smith, B. (2002). Onions—a global benefit to health. *Phytotherapy Research: An International Journal Devoted to Pharmacological and Toxicological Evaluation of Natural Product Derivatives*, *16*(7), 603-615. https://doi.org/10.1002/ptr.1222

Halvorson, A. D., Bartolo, M. E., Reule, C. A., & Berrada, A. (2008). Nitrogen effects on onion yield under drip and furrow irrigation. *Agronomy Journal*, *100*(4), 1062-1069. https://doi.org/10.2134/agronj2007.0377

Hartz, T. K., & Johnstone, P. R. (2006). Nitrogen availability from high-nitrogen-containing organic fertilizers. *HortTechnology*. *16*(1), 39-42. https://doi.org/10.21273/HORTTECH.16.1.0039

Heath, O. V. S., & Holdsowrth, M. (1948). Morphogenic factors as exemplified by the onion plant. In *Society of the Experiment Biology, Symposia*.

Kato, T. (1964). Physiological studies on the bulbing and dormancy of onion plant. III. Effects of external factors on the bulb formation and development. *Journal of the Japanese Society for Horticultural Science*, *33*(1), 53-61. https://doi.org/10.2503/jjshs.33.53

Kim, H. Y., Jackson, D., Adhikari, K., Riner, C., & Sanchez-Brambila, G. (2017). Relationship Between Consumer Acceptability and Pungency-Related Flavor Compounds of Vidalia Onions. *Journal of food science*, *82*(10), 2396-2402. https://doi.org/10.1111/1750-3841.13915

Lancaster, J. E., & Boland, M. J. (1990). Flavor biochemistry In Brewster, J. L., Rabinowitch, H. D. (eds), *Onions and Allied Crops* (pp. 33-72). CRC Press, Boca Raton, FL, USA.

Lancaster, J. E., Shaw, M. L., & Randle, W. M. (1998). Differential hydrolysis of alk (en) yl cysteine sulphoxides by alliinase in onion macerates: flavour implications. *Journal of the*

Science of Food and Agriculture, *78*(3), 367-372. https://doi.org/10.1002/(SICI)1097-0010(199811)78:3%3C367::AID-JSFA127%3E3.0.CO;2-N

Machado, R. M. A., Shahidian, S., Pivetta, C. R., & Oliveira, M. (2009). Nitrogen fertilization effects on rooting pattern and yield of intermediate-day onions bulb in Alentejo region. *Revista de Ciências Agrárias*, *32,* 113-122. https://doi.org/10.19084/rca.15731.

Olsson, T. C. (2012). Peeling Back the Layers: Vidalia Onions and the Making of a Global Agribusiness. *Enterprise & Society*, *13*(4), 832-861. https://doi.org/10.1093/es/khs008

Organic trade association. (2023). Organic food sales break through $60 billion in 2022. https://ota.com/news/press-releases/22820 (accessed 4 Oct. 2023).

Petropoulos, S. A., Ntatsi, G., & Ferreira, I. C. F. R. (2017). Long-term storage of onion and the factors that affect its quality: A critical review. *Food Reviews International*, *33*(1), 62-83. https://doi.org/10.1080/87559129.2015.1137312

Randle, W. M. (1997). Onion flavor chemistry and factors influencing flavor intensity. In Risch, S. J., & HO, C. (Eds*), Spices: Flavor Chemistry and Antioxidant Properties.* American Chemical Society, Washington, DC.

Randle, W. M. (2000). Increasing nitrogen concentration in hydroponic solutions affects onion flavor and bulb quality. *Journal of the American Society for Horticultural Science*, *125*(2), 254-259. https://doi.org/10.21273/JASHS.125.2.254

Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature plants*, *2*(2), 1-8. https://doi.org/10.1038/nplants.2015.221

Schwimmer, S., & Weston, W. J. (1961). Onion flavor and odor, enzymatic development of pyruvic acid in onion as a measure of pungency. *Journal of Agricultural and Food Chemistry*, *9*(4), 301-304.

Sharma, K., Asnin, L., Ko, E. Y., Lee, E. T., & Park, S. W. (2015). Phytochemical composition of onion during long-term storage. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, *65*(2), 150-160. https://doi.org/10.1080/09064710.2014.983151

Stumpf, S., Gitaitis, R., Coolong, T., Riner, C., & Dutta, B. (2017). Interaction of onion cultivar and growth stages on incidence of Pantoea ananatis bulb infection. *Plant Disease*, *101*(9), 1616-1620. https://doi.org/10.1094/PDIS-01-17-0143-RE

Strydom, E. (1964). A root study of onions in an irrigation trial. *South African Journal of Agricultural Science*, *7*(4), 593-601. https://hdl.handle.net/10520/AJA05858860_329

Taiz, L., & Zeiger, E. (2006). *Plant physiology and development* (5th edition). Sinauer Associates, Sunderland, MA.

Tekalign, T., Abdissa, Y., & Pant, L. M. (2012). Growth, bulb yield and quality of onion (Allium cepa L.) as influenced by nitrogen and phosphorus fertilization on vertisol. II: Bulb quality and storability. *African Journal of Agricultural Research*, *7*(45), 5980-5985. https://doi.org/10.5897/AJAR10.1024

University of Georgia. (2022). 2021 Georgia farm gate value report. *University of Georgia Cooperative Extension Bulletin* AR 22-01. https://caed.uga.edu/publications/farm-gate-value.html (accessed 25 ago 2023).

US Department of Agriculture, National Agricultural. (2023). Vegetables 2022 Summary. https://usda.library.cornell.edu/concern/publications/02870v86p?locale=en (accessed 23 ago 2023)

Walcott, R.R., Gitaitis, R.D., Castro, A.C., Sanders, F.H. Jr., and Diaz-Perez, J.C. 2002. Natural infestation of onion seed by Pantoea ananatis, causal agent of center rot. Plant Dis. 86:106-111.

Walcott, R. R., Gitaitis, R. D., Castro, A. C., Sanders Jr, F. H., & Diaz-Perez, J. C. (2002). Natural infestation of onion seed by Pantoea ananatis, causal agent of center rot. *Plant disease*, *86*(2), 106-111. https://doi.org/10.1094/PDIS.2002.86.2.106

Yoo, K. S., Lee, E. J., & Patil, B. S. (2012). Changes in flavor precursors, pungency, and sugar content in short-day onion bulbs during 5-month storage at various temperatures or in controlled atmosphere. *Journal of food science*, *77*(2), C216-C221. https://doi.org/10.1111/j.1750-3841.2011.02529.x

CHAPTER 3

IMPACT OF NITROGEN FERTILIZER RATE AND TIMING ON SHORT-DAY ONION PRODUCTION[1]

[1] de Jesus, H. I., da Silva, A. L. B. R., Dutta, B., & Coolong, T. (2023). Accepted by *HortTechnology* (with minor revision).

Abstract

Short-day onions (*Allium cepa*) are typically planted late fall and harvested in spring in the Vidalia, Georgia, USA region. This onion is known for its sweetness and is popularly known as the Vidalia onion. High rainfall during the relatively long growing season (4 to 5 months) may result in nitrogen (N) leaching during production. Therefore, fertilizer applications are usually split into multiple stages during crop development to ensure soil nutrient availability during the entire season. While the impacts of season total N rate applications have been previously investigated in Vidalia onion production, the optimal timing for the final N fertilizer of the season application has not been determined. Thus, the objective of this study was to evaluate the timing of the last fertilizer N application (at bulb initiation, during bulb growth, or during bulb maturation) in conjunction with the impact of three N application rates (75, 105 and 135 lb/acre N) combined in a two factorial experimental design arranged in a randomized complete block design in 2020 and 2021 in Georgia, USA. Nitrogen application rate had a greater impact on yield in 2020 compared to 2021 due to variable soil N levels caused by excessive rainfall, emphasizing the importance of adjusting N rates based on seasonal rainfall patterns. Final N applications at bulb initiation were found to increase the production of jumbo-sized onions. Incidence of sour skin (*Burkholderia cepacia*) and center rot (*Pantoea* spp.) diseases were greater in 2020 compared to 2021 but were not significantly affected by N rates or application timing. Final N applications during bulb maturation were associated with increased pungency levels when season total rates of N were 75 lb/acre N. Generally, as fertilizer N rate increased and as the time of last N application was later, pungency values increased.

Introduction

Onions (*Allium cepa*) are among the highest valued vegetables grown in the United States (US), with $1.6 billion in value obtained from 127,200 of acres of production reported by the US Department of Agriculture (USDA) in 2022 (USDA, 2022). In the southeastern US, the state of Georgia, USA is recognized for the production of Vidalia onions, where over 11,000 acres were grown in 2021 with an estimated farm gate value of $167 million, accounting for approximately 13% of the Georgia's vegetable farm-gate income (University of Georgia, 2022). Vidalia onions are exclusively grown in the southeastern region of the state, where the combination of mild winters, low sulfur soils, and ample water supply creates ideal conditions for cultivating of sweet and mild onions (Boyhan & Torrance, 2002).

The successful production of onions depends on the soil nitrogen (N) availability throughout crop development (Brewster, 2008). Onions have a shallow root system, in which most roots are found in the top 6 inches of soil (Halvorson et al., 2002; Strydom, 1964). This long production season and shallow root system create challenges of producers as water and nutrients are easily leached from the rootzone of onion (Sharma et al., 2012), which are grown in the sandy loam soils of the Coastal Plain region of southeastern Georgia, USA (Boyhan & Torrance, 2002).

Significant research has been conducted to determine the appropriate levels of N fertilization to optimize the yield and quality of Vidalia onions (Batal et al., 1994; Boyhan et al., 2007; Díaz Peréz et al., 2003). Previous studies have highlighted the benefits of splitting the total recommended N into multiple applications throughout the growing season (Boyhan et al., 2007; Coolong & Boyhan, 2017; da Silva et al., 2022). Typically, the first N application occurs at transplanting, followed by a second application during the early vegetative growth stage [50 d after transplant (DAT)] to promote root and leaf growth. The remaining N is typically divided into two additional applications in the latter half of the season.

Because N assimilation is greatest during bulb development (Geisseler et al., 2022), applications of N late in the season may significantly impact onion bulb quality to a greater degree than early season N applications (Geisseler et al., 2022). Increased soil N levels can also lead to elevated bulb pungency, reducing the perceived sweetness of onions (Greenwood et al. 1980; Randle 2000). Reductions in bulb quality during storage have been reported when N is applied during bulb maturation (Batal et al., 1994; Coolong & Randle, 2008; Randle, 2000; Tekalign et al., 2012). Additionally, increased soil N levels during bulb maturation have been reported to increase susceptibility to some bacterial pathogens (Díaz-Perez et al., 2003). However, late applications of N fertilizers in onion can increase N fertilizer use efficiency and creates opportunities to decrease the overall N fertilization rates (de Jesus et al., 2023a). Therefore, the objective of this study was to evaluate the effects of the timing of the last N fertilizer application for the season in combination with three N fertilizer rates on the yield and quality of short-day onions.

Materials & Methods

Field experiments were conducted in the 2020 and 2021 Vidalia onion seasons at the University of Georgia (UGA) Vidalia Onion and Vegetable Research Center located in Lyons, GA, USA (*32°00′*58″ *N*, *82°13′*17″ *W*). The region is classified as having a humid subtropical climate and the soil is characterized as an Irvington Sandy Loam (USDA, 2023) with 0.6% organic matter, 2% slope, and low water holding capacity.

Seeds of short-day onions ‘Candy Ann’ (Solar Seeds, Bangalore, India) were grown in nursery beds for approximately 8 weeks. Seedlings were removed from transplant beds by hand

and foliage cut to a length of approximately 4-5 inches. Bareroot seedlings were then transplanted to the field on 15 Dec 2019 and 10 Dec 2020. Fields were prepared by harrowing the soil to a depth of approximately 10 inches, followed by final tillage and bed formation using a tractor mounted rotary tiller. Beds were approximately 6-inches tall and spaced at 6-ft center to center, with each bed having four onion rows spaced 10-inches apart, with an in-row spacing of 4 inches between plants (87,120 plants/acre). Experimental plots were 30-ft long containing approximately 360 plants each.

A split-plot arrangement with three N fertilizer rates and three final fertilizer N application times were evaluated in a randomized complete block design with eight replications in both years. Fertilizer rate treatments consisted of season-long totals of 75, 105, 135 lb/acre N. Beginning at transplanting all plots received an application of 20% of their season total N, which corresponded to 15, 21, and 27 lb/acre N (5.0N-4.4P-12.5K, Rainbow Plant Food, Timac Agro USA, Reading, PA, USA), representing the 75, 105, and 135 lb/acre N treatments, respectively. Two additional applications of 15, 21, and 27 lb/acre N (5.0N-4.4P-12.5K, Rainbow Plant Food, Timac Agro USA) were made on 23 (2020) or 27 (2021) DAT and 47 (2020) or 49 (2021) DAT, which corresponded to early vegetative and late vegetative growth stages of development, respectively. The final N application consisted of 40% of the season total N application, corresponding to 30, 42, and 54 lb/acre N using calcium nitrate (15.5N-0P-0K, Yara Liva, Yara North America, Tampa, FL, USA). The final N application was conducted during bulb initiation, during bulb development, or bulb maturation, corresponding to 64, 74, and 84 DAT in 2020, and 68, 78, and 88 DAT in 2021, respectively.

In both growing seasons, onions were overhead irrigated using stationary sprinklers. Irrigation water volume was determined based on historic onion evapotranspiration and accumulated rainfall. Air temperatures and precipitation were monitored and recorded every 15 min using a nearby on-farm weather station from the UGA Weather Network (UGA, 2022). Pre-emergent herbicides oxyfluorfen (0.49 lb/acre) (Goal 2xL; NuFarm, Alsip, IL, USA) and pendimethalin (0.82 lb/acre) (Prowl 3.3EC; BASF, Research Triangle Park, NC, USA) were broadcast applied over onion transplants within 7 DAT in both years. Routine fungicide and insecticide applications were made weekly during the season according to recommendations for the region (Sial et al., 2022).

Soil Mineral N Availability

Soil samples were collected before each fertilizer application and at harvest in 2020 (0, 23, 47 and 71, and 129 DAT) and 2021 (5, 27, 49, 68, and 131 DAT) to determine the soil mineral N content. Soil samples were comprised of five sub-samples collected in each plot at a 0–15 cm soil depth. After sampling, composite samples were homogenized, air dried, and tested for soil mineral N content [ammonium (NH_4^+) and nitrate (NO_3^-)] at a commercial laboratory (Waters Agricultural Laboratories, Camilla, GA, USA).

Short-Day Onion Harvesting and Bulb Quality

Onions were harvested when approximately 50% of the plants had evidence of pseudostem lodging (tops down), which occurred at 128 DAT in 2020 and 131 DAT in 2021. At harvest onion tops and roots were manually cut, and bulbs were cured for 1 week with forced air at 38 °C. Subsequently, bulbs were graded into colossal (> 3.75 inches), jumbo (3.25 to 3.75 inches), and medium (< 3.25 inches) sizes following the standards for grades of Bermuda-Granex-Grano type onions (USDA, 2014). Marketable yields were calculated as the sum of colossal, jumbo, and medium bulbs. After harvest, onions were evaluated for sour skin (*Burkholderia cepacia*) and center rot (*Pantoea* spp.), in which 20 jumbo-sized onions were cut longitudinally and the percentage of bulbs with visual symptoms of center rot and sour skin damage were determined.

Onion pungency measured as pyruvic acid was determined from a sample of five jumbo-sized onions. The neck, root plates, and dry outer scales of onion bulbs were removed and the remaining whole onions were blended for juice extraction using a household blender. A 1.5 ml liquid sample was removed from the blended sample and stored at -20 °C until analysis. The frozen samples were defrosted, and 20 uL of onion juice was used to determine the pyruvic acid content according to Lancaster & Boland (1990).

Statistical Analysis

Data were analyzed using the Standard Least Squares method from JMP Pro 16.0 (SAS Institute Inc., Cary, NC). Total yield, bulb grade (colossal, jumbo, and medium), and bulb quality (i.e., sour skin incidence, center rot incidence and pungency) were analyzed with total fertilizer N rate (75, 105, 135 lb/acre N), last N application (at bulb initiation, during bulb development, or during bulb maturation), year (2020 and 2021), and their interactions as fixed effects. Soil N content was analyzed with fertilizer N rate treatments, last application timing, year, sampling time (0, 23, 47, 71 and 129 DAT in 2020, and 5, 27, 49, 68 and 131 DAT in 2021), and their interaction as main effects. In both analyses, block was treated as a random effect. When the F value of the ANOVA was significant, multiple mean comparisons were performed using the Tukey's Honest Significant Difference Test ($P<0.05$).

Results

Weather Conditions

During the study there were 29.7 and 20.9 inches of rainfall in 2020 and 2021, respectively (Figure 3.1). In 2020, rainfall events were evenly distributed during the early season, with 5.3

inches of precipitation from transplanting to early vegetative stages of growth (21 DAT), and 3 inches from early vegetative to late vegetative stages (47 DAT). During bulb initiation, there were fewer but larger rainfall events with a total of 21.5 inches of precipitation. In 2021, there were 15.8 inches of rainfall from transplanting to bulb development (78 DAT) and 5.1 inches of rainfall from bulb development to harvest (131 DAT).

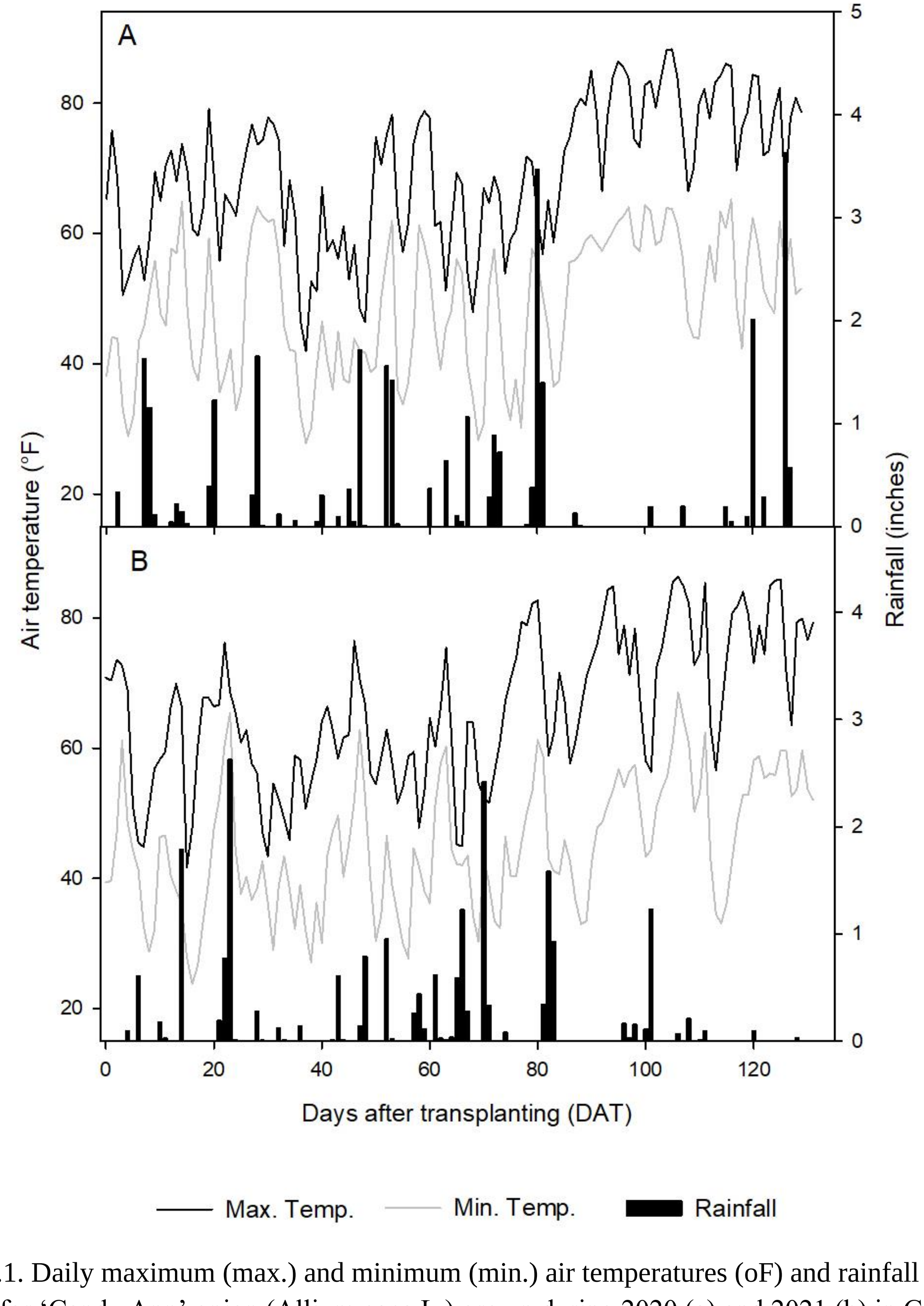

Figure 3.1. Daily maximum (max.) and minimum (min.) air temperatures (oF) and rainfall (inches) for 'Candy Ann' onion (Allium cepa L.) grown during 2020 (a) and 2021 (b) in Georgia, USA. Data averages estimated using the University of Georgia Weather Network; (°F - 32) ÷ 1.8 = °C, 1 inch = 2.54 cm.

In 2020, average minimum and maximum air temperatures were 34 °F and 76 °F, respectively. Average minimum and maximum air temperatures were 34 °F and 74 °F, respectively in the 2021 season (data not shown). Although season average air temperatures were similar between the two seasons, there were more nights with temperatures below freezing in 2020 than 2021, particularly in the first 2 months of the study (Figure 3.1).

Soil mineral N concentrations

Soil mineral N concentrations were affected by a year and fertilizer rate interaction (Figure 3.2). In 2020, soil mineral N concentrations differed between the N application rate treatments, with the 135 lb/acre N having significantly higher soil mineral N concentrations of 6 and 17 lb/acre N at 23 and 47 DAT, respectively, compared to the 75 and 105 lb/acre N treatments. Soil mineral N concentrations decreased for all treatments later in the season, and no significant differences were seen among N fertilizer rates at any other sampling time in 2020. In contrast, soil mineral N concentrations were the highest early in the season in 2021, and significant differences were measured among N rates at 27 DAT, with the 135 lb/acre N having a significantly higher soil N concentration (19 lb/acre N) than the applications of 75 and 105 lb/acre N, respectively. Soil mineral N concentrations decreased at 68 DAT, but significant differences remained among fertilizer N rate treatments, with the highest soil N concentration of 8 lb/acre N being measured for the application of 135 lb/acre N.

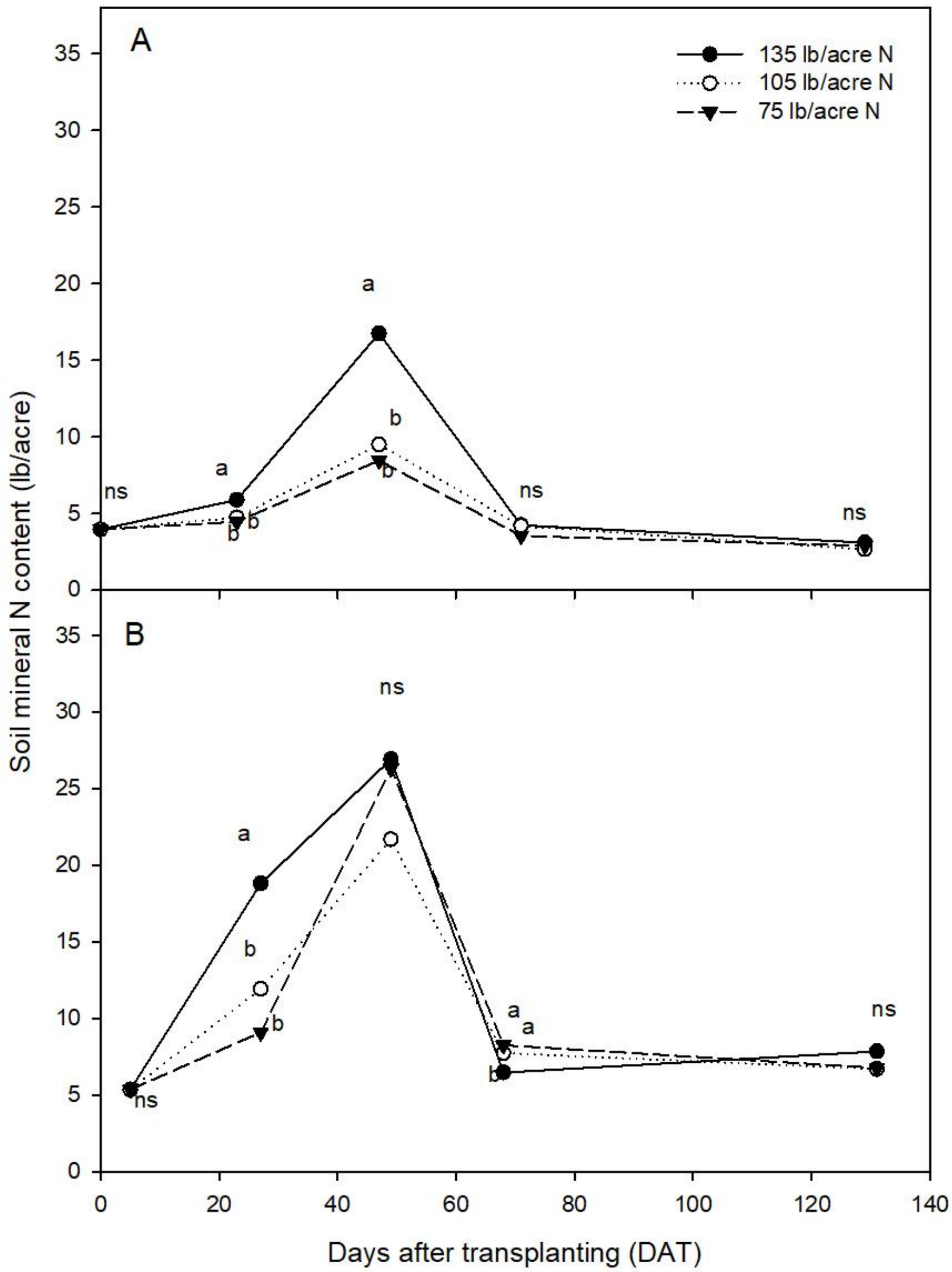

Figure 3.2. The effects of 135, 105 and 75 lb/acre nitrogen (N) on soil mineral N concentrations at 0, 23, 47 and 71, and 129 (harvest) DAT in 2020 (A), and at 5, 27, 49, 68, and 131 (harvest) DAT in 2021 (B) for 'Candy Ann' onion (Allium cepa L.) grown in Georgia, USA; 1 lb/acre =1.1209 $kg·ha^{-1}$.

Soil mineral N concentrations at harvest were affected by the interaction of year and timing of the last N fertilizer application (Figure 3.3). In general, soil mineral N concentrations were significantly lower in 2020 compared to 2021 (data not shown). In 2020, there were no differences in soil mineral N concentrations among the last N application treatments. However, soil mineral N concentration at harvest in 2021 was significantly higher (8.4 lb/acre N) with the last N application at bulb growth compared to the last N application at bulb initiation (5.9 lb/acre N) or during bulb maturation (6.9 lb/acre N).

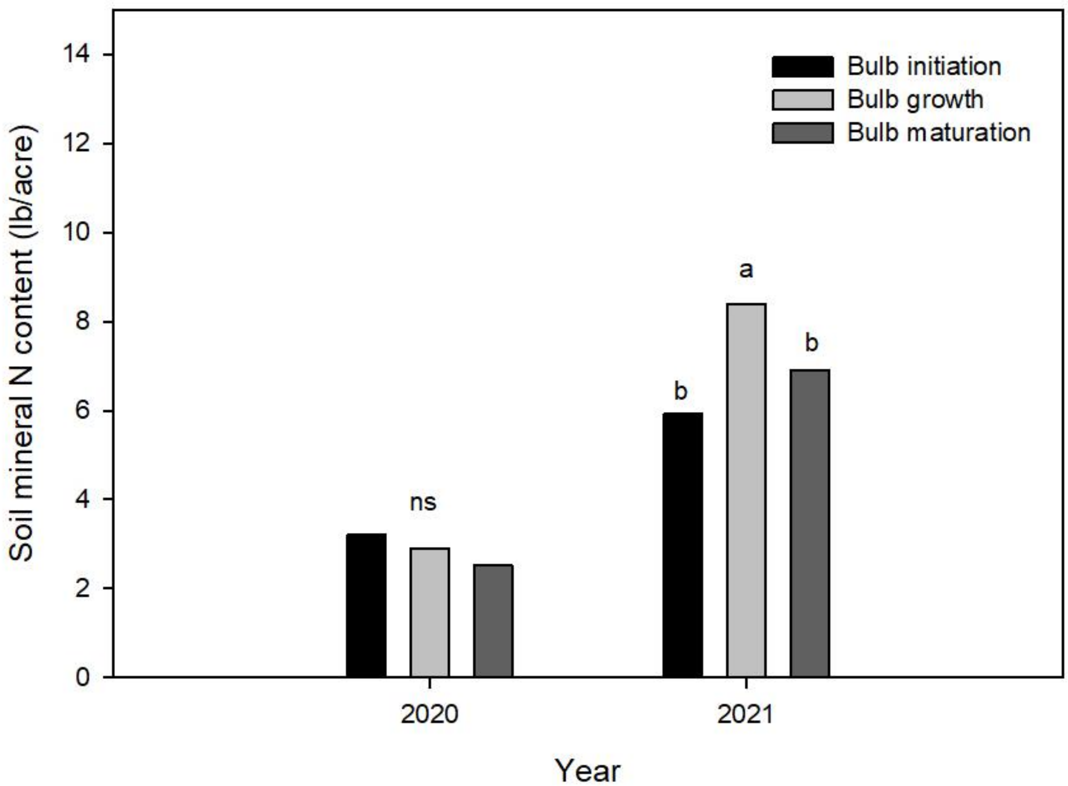

Figure 3.3. Effect of timing of the last fertilizer nitrogen (N) application on soil mineral N content at harvest in 2020 and 2021 in Georgia, USA; 1 lb/acre =1.1209 kg·ha-1.

Onion yields

Marketable yield and yield of colossal, jumbo, and medium bulbs were impacted by the interaction between year and N rate (Table 3.1). In 2020, marketable yield of onions increased as the N fertilizer rate increased from 75 to 135 lb/acre N, resulting in yields of 38,905 and 50,968 lb/acre, respectively. However, in 2021, there was no significant difference in marketable yield of onions among N fertilizer rates.

Table 3.1. Interaction between year and fertilizer nitrogen (N) rate on marketable yield and yield of colossal, jumbo, and medium onions (*Allium cepa*) grown in Georgia, USA in 2020 and 2021.

N rate (lb/acre)	2020				2021			
	Marketable	Colossal	Jumbo	Medium	Marketable	Colossal	Jumbo	Medium
	Yield (lb/acre)[i]							
75	38,905 A c[ii]	817 A b	31,896 A c	6192 B a	39,567 A a	161 B a	27,880 B a	11,525 A a
105	44,682 A b	1413 A b	38,121 A b	5149 B b	41,523 A a	282 B a	30,986 B a	10,255 A a
135	50,968 A a	3926 A a	43,239 A a	3802 B b	43,227 B a	393 B a	32,509 B a	10,325 A a

[i]1 lb/acre =1.1209 kg·ha^{-1}.

[ii]Different uppercase letter represents significant differences between Year, and different lowercase letter represents significant differences between N rate according to the Tukey test (P<0.05).

The yield of colossal bulbs was greater in 2020 compared to 2021, regardless of N fertilizer rate. In 2020 there was an increase of colossal-sized onions with the application of 135 lb/acre N (3,926 lb/acre), whereas no significant differences were measured among the applications of 105 lb/acre N (1413 lb/acre) and 75 lb/acre N (817 lb/acre). In 2021, N fertilizer rates did not significantly affect the yield of colossal bulbs. The yield of jumbo-sized onions was also significantly higher in 2020 compared to 2021, regardless of the N fertilizer rate applied. The yield of jumbo-sized onions was influenced by N rate only in 2020. Specifically, the lowest N application rate of 75 lb/acre N had the lowest yield of jumbo bulbs compared to the application of 105 or 135 lb/acre N. In contrast to the other onion sizes, the yield of medium-sized onions was greater in 2021 compared to 2020. In 2020, the lowest N application rate of 75 lb/acre N had a higher yield of medium-sized onions compared to the other N application rates, whereas there was no significant difference among fertilizer N treatments in 2021.

There was no interaction between the timing of the last N application and fertilizer rate or year for total marketable yield of onion. However, timing of the last N application had a significant effect on marketable yield and bulb size distribution (Table 3.2). Marketable yield was higher when the last N fertilizer application occurred at bulb initiation (44,747 lb/acre) than during bulb growth (43,170 lb/acre) or during bulb maturation (41,520 lb/acre). Similar results were measured for the yield of jumbo-sized onions, with the final N fertilizer application at bulb initiation resulting in a greater yield (36,611 lb/acre) than when applied at bulb maturation (31,661 lb/acre). The timing of application did not affect the yield of colossal-sized bulbs.

Table 3.2. Effects of the stage of development for the timing of last fertilizer nitrogen (N) on total, colossal, jumbo and medium onion (*Allium cepa*) yields in Georgia, USA in 2020 and 2021.

Stage of development	Total	Colossal	Jumbo	Medium

	Yield (lb/acre)[i]							
Bulb initiation	44,747	a[ii]	1272	a	36,611	a	172	b
Bulb growth	43,170	b	1205	a	34,044	ab	198	a
Bulb maturation	41,520	b	1019	a	31,661	b	221	a

[i]1 lb/acre =1.1209 kg·ha^{-1}.

[ii]Values followed by the same letter(s) indicate no significant difference according to the Tukey's honest significant difference test (P<0.05).

Bulb quality

The incidence of center rot and sour skin was not affected by interactions between fertilizer N rate, timing of last application, and year. However, center rot and sour skin incidence were impacted by the main effect of year, in which there was a significantly higher incidence of center rot (5.5%) and sour skin (1.5%) in 2020 compared to 2021 (Table 3.3). Fertilizer N rate and timing of last application timing had no impact on incidence of onion sour skin and center rot.

Table 3.3. Main effects of year, fertilizer nitrogen (N) rate, and stage of development of the last fertilizer N application on the incidence of center rot (*Pantoea* spp.) and sour skin (*Burkholderia cepacia*) for onion (*Allium cepa*) grown in Georgia, USA in 2020 and 2021.

Treatments	Center rot		Sour skin	
	%			
Year				
2020	5.5	a[i]	1.5	a
2021	0.6	b	0.0	b
N rate (lb/acre)				
75	2.74	a	0.73	a
105	3.71	a	0.63	a
135	2.67	a	0.94	a
Stage of development				
Bulb initiation	2.15	a	0.31	a
Bulb growth	3.34	a	1.15	a
Bulb maturation	3.63	a	0.83	a

[i]Values followed by the same letter(s) indicate no significant difference according to Tukey's honest significant difference test (P<0.05).

Onion pyruvic acid concentration (pungency) was affected by the interaction between N fertilizer rate and the timing of last N fertilizer application (Table 3.4). Onion pungency was lowest in plants receiving 75 lb/acre N with the last N application at bulb initiation. However, as fertilizer N rate increased and as the time of last N application was later, pungency also increased. In general, onion pungency was significantly higher in 2020 (6.28 µmol) compared to 2021 (4.20 µmol) (data not shown).

Table 3.4. Effect of the interaction between nitrogen (N) rate and the stage of development of the last fertilizer N application on the pyruvic acid concentration (pungency) of onion (*Allium cepa*) grown in Georgia, USA in 2020 and 2021.

N (lb/acre)	Stage of development		
	Bulb initiation	Bulb growth	Bulb maturation
	Pungency (µmol)		
75	4.64 B b[i]	5.32 A ab	5.48 A a
105	5.14 AB a	5.55 A a	5.23 A a
135	5.31 A a	5.08 A a	5.31 A a

[i]Different lowercase letter represents significant differences between stage of development of the last N application, and different uppercase letter represents significant differences between N rate according to Tukey's honest significant difference test (P<0.05).

Discussion

Rainfall has historically impacted fertilizer N management for vegetable production in the southeastern US (da Silva et al., 2020; de Jesus et al., 2023b; Zoratelli et al., 2015), which includes Vidalia onions (da Silva et al. 2022). Differences in rainfall patterns have been shown to result in variable responses of soil mineral N concentrations (Cavero et al., 1999; Gu & Riley, 2010;

Hasegawa & Denison, 2004). In the present study there was generally a lower level of soil mineral N in 2020 compared to 2021 (Figure 3.3). Soil mineral N concentrations in 2021 ranged between 9 and 19 lb/acre N at 27 DAT, while soil mineral N averaged 5 lb/acre N for all three fertilizer treatments at 23 DAT in 2020. Soil mineral N levels increased in 2021 to an average of 25 lb/acre N at 49 DAT, while they ranged between 9 and 18 lb/acre N in 2020, suggesting that more soil mineral N was available to plants prior to bulbing in 2021. Soil mineral N levels were also impacted by the fertilizer rate N treatments. In 2020 the application of 135 lb/acre N increased yields compared to the application of 75 and 105 lb/acre N. The primary reason for this increase in yield was the greater yield of colossal-sized bulbs, which doubled as the N fertilizer rate increased from 105 to 135 lb/acre N. In 2021 rainfall was evenly distributed through the season, with fewer rainfall events that could potentially result in the leaching of excessive fertilizer N from the soil. This favorable rainfall pattern may have contributed to a more efficient utilization of the applied fertilizer N in the soil. In 2021 there were no differences in total marketable yield among N fertilizer rate treatments, suggesting that 75 lb/acre N was sufficient to achieve commercially acceptable onion yields under these specific weather conditions. These findings agree with the results reported by da Silva et al. (2022), supporting the effectiveness of lower N fertilizer rates in achieving satisfactory onion yields in Georgia, USA, although fertilizer N rate should be adjusted according to rainfall patterns during the growing season.

Marketable yields for all fertilizer rates were comparable to or higher than expected commercial yields for the region (Coolong & Boyhan 2017). Fertilizer N rate did impact marketable onion yields; however, fertilizer N rate should be adjusted according to rainfall patterns. For instance, as fertilizer rate increased from 75 to 135 lb/acre N in 2020, when rainfall events were elevated, marketable yields as well as yield of jumbo bulbs increased. However, when there were few rainfall events in 2021, there were no differences in marketable yields among fertilizer N rate treatments. While the 135 lb/acre N rate led to potentially higher yields in 2020, it is worth noting that growers prioritize jumbo-sized bulbs due to their higher market value compared to colossal and medium-sized onions (Tyson, C, personal communication) and the results indicated no significant differences in the yield of jumbo bulbs for N fertilizer rates higher than 105 lb/acre N.

The timing of the last fertilizer N application significantly influenced onion marketable yields, with applications at bulb initiation leading to increased marketable and jumbo-bulb yields, while later applications during bulb growth or maturation resulted in lower yields. This observation suggests that growers can optimize their final N applications by synchronizing them with the bulb initiation stage of growth, potentially improving fertilizer N use efficiency and enhancing overall yield and quality (Geisseler et al., 2022). Recent findings by de Jesus et al. (2023a) further support this, showing increased fertilizer N use efficiency when N is applied during bulb initiation, but reduced N uptake when the final application is delayed until bulb growth.

Symptoms of sour skin and center rot diseases were observed in onions grown in 2020, but not in 2021 and they were not affected by fertilizer rate or the timing of the last N application. da Silva et al. (2022) reported similar results, with no significant differences for sour skin and center rot incidence among fertilizer N application rates ranging from 75 to 135 lb/acre N. These results contrast with previous research suggesting that high N rates and late fertilizer N application can increase incidence of bacterial disease in onions (Batal et al., 1994; Wright, 1993). It is notable that when only data from 2020 were analyzed, when incidence of center rot was 5.5%, there was an effect of the timing of the last N application on center rot incidence (data not shown). In that season, final N applications at bulb initiation resulted in a significantly lower rate of center rot

(2.30%) than applications during bulb swelling (6.25%) and maturation (6.67%) (data not shown). However, when both 2020 and 2021 data were analyzed, there was no significant impact of N rate, application time, or their interaction on the incidence of center rot in bulbs (Table 3.3). Increased disease incidence in 2020 may have been related to increased rainfall in the weeks leading up to harvest. Onions are vulnerable to bacterial infection near harvest when the neck retains more water, creating a conducive environment for pathogens (Brewster, 2008; Stumpf et al., 2021). In seasons when weather conditions are more conducive for bacterial diseases there may be an impact of N timing on severity of some pathogens; however, this effect may be inconsistent as our data suggest.

Fertilizer N rate and the timing of last fertilizer N application interacted to affect onion pungency. While previous studies have extensively explored the effect of high N fertilization on onion pungency, the effect of the timing of last fertilizer N application is limited (Coolong & Randle, 2003; McCallum et al., 2005; Randle, 2000). In the present study, onions receiving the lowest N rate of 75 lb/acre N, with the last fertilizer N application being delayed until during bulb maturation had a greater bulb pungency compared to when the last fertilize N application was made at bulb initiation. This suggests that later fertilizer N applications, specifically after the bulbing stage of development, may contribute to increased pungency in onions. Therefore, the late N fertilizer applications should also be carefully managed when cultivating onions for specific flavor attributes.

Conclusion

This study aimed to evaluate the effects of fertilizer N rates and timing of the last fertilizer N application in the production of short-day onions in the Georgia, USA. Fertilizer N rate had a greater impact on yield in 2020 compared to 2021, likely due to variations in soil mineral N accumulation. In 2020, excessive rainfall reduced soil N availability, and yield increased at the highest fertilizer N rate (135 lb/acre N). In contrast, the evenly distributed rainfall in 2021 likely allowed for a more efficient utilization of the applied fertilizer and yields were comparable across fertilizer N rate treatments. The timing of N fertilizer application also influenced yield, with early application at bulb initiation resulting in more jumbo-sized onions. In conclusion, short-day onions cultivated in the southeastern US may require 135 lb/acre N or more during years with high levels of precipitation, while in years with less rainfall, N rates as low as 75 lb/acre N may result in yields that are comparable to onions grown with up to 135 lb/acre N. Additionally, the final application of N should occur at bulb initiation to maximize yield and flavor potential.

Literature Cited

Batal, K. M., Bondari, K., Granberry, D. M., & Mullinix, B. G. (1994). Effects of source, rate, and frequency of N application on yield, marketable grades and rot incidence of sweet onion (Allium cepa L. cv. Granex-33). *Journal of Horticultural Science, 69*(6), 1043-1051. https://doi.org/10.1080/00221589.1994.11516543

Boyhan, G. E., & Torrance, R. L. (2002). Vidalia Onions – Sweet Onion Production in Southeastern Georgia. HortTechnology. 12(2),196–202. https://doi.org/10.21273/HORTTECH.12.2.196

Boyhan, G. E., Torrance, R.L., & Hill, C. R. (2007). Effects of nitrogen, phosphorus, and potassium rates and fertilizer sources on yield and leaf nutrient status of short-day onions. HortScience. 42(3),653–660. https://doi.org/10.21273/HORTSCI.42.3.653

Brewster, J. L. (2008). Onions and other vegetable alliums (2nd ed). CABI, Wellesbourne, UK.

Cavero, J., Plant, R. E., Shennan, C., Friedman, D. B., Williams, J. R., Kiniry, J. R., & Benson, V. W. (1999). Modeling nitrogen cycling in tomato–safflower and tomato–wheat rotations. *Agricultural systems, 60*(2), 123-135. https://doi.org/10.1016/S0308-521X(99)00023-2

Coolong, T., & Boyhan, G. (2017). Onion production guide. *University of Georgia Cooperative Extension Bulletin* 1198.

Coolong, T. W., Kopsell, D. A., Kopsell, D. E., & Randle, W. M. (2005). Nitrogen and sulfur influence nutrient usage and accumulation in onion. *Journal of plant Nutrition, 27*(9), 1667-1686. https://doi.org/10.1081/PLN-200026010

Coolong, T. W., & Randle, W. M. (2003). Ammonium nitrate fertility levels influence flavour development in hydroponically grown 'Granex 33'onion. *Journal of the Science of Food and Agriculture, 83*(5), 477-482. https://doi.org/10.1002/jsfa.1398

Coolong, T. W., & Randle, W. M. (2008). The effects of calcium chloride and ammonium sulfate on onion bulb quality at harvest and during storage. *HortScience. 43*(2), 465-471. https://doi.org/10.21273/HORTSCI.43.2.465.

da Silva, A. L. B. R., Coolong, T., & Smith, E. (2019). Irrigating. University of Georgia. https://irrigating.uga.edu/ [accessed 22 May 2023].

da Silva, A. L. B. R., Candian, J. S., Zotarelli, L., Coolong, T., & Christensen, C. (2020). Nitrogen fertilizer management and cultivar selection for cabbage production in the southeastern United States. *HortTechnology, 30*(6), 685-691. https://doi.org/10.21273/HORTTECH04690-20

da Silva, A. L. B. R., Rodrigues, C., Dunn, L., Cavender, G., & Coolong, T. (2022). Fertilizer nitrogen application for short-day onion production: from field to table. *Horticulturae. 8*(9), 847. https://doi.org/10.3390/horticulturae8090847

de Jesus, H. I., da Silva, A. L. B. R., Cassity-Duffey, K., & Coolong, T. (2023a). Estimating fertilizer nitrogen-use efficiency in transplanted short-day onion. *Nitrogen.* 4(3), 286-295. https://doi.org/10.3390/nitrogen4030021

de Jesus, H. I., da Silva, A. L. B. R., Dutta, B., Cassity-Duffey, K., & Coolong, T. (2023b). Influence of organic fertilizer sources and application rates on onion production in Georgia, USA. *HortTechnology. 33*(4), 398-406.

Díaz-Pérez, J. C., Purvis, A. C., & Paulk, J. T. (2003). Bolting, yield, and bulb decay of sweet onion as affected by nitrogen fertilization. *Journal of the American Society for Horticultural Science, 128*(1), 144-149.

Geisseler, D., Ortiz, R. S., & Diaz, J. (2022). Nitrogen nutrition and fertilization of onions (Allium cepa L.)–A literature review. *Scientia Horticulturae, 291*. https://doi.org/10.1016/j.scienta.2021.110591

Greenwood, D. J., Cleaver, T. J., Turner, M. K., Hunt, J., Niendorf, K. B., & Loquens, S. M. H. (1980). Comparison of the effects of nitrogen fertilizer on the yield, nitrogen content and quality of 21 different vegetable and agricultural crops. *The Journal of Agricultural Science*, *95*(2), 471-485. https://doi.org/10.1017/S0021859600039514

Gu, C., & Riley, W. J. (2010). Combined effects of short-term rainfall patterns and soil texture on soil nitrogen cycling—A modeling analysis. *Journal of contaminant hydrology*, *112*(1-4), 141-154. https://doi.org/10.1016/j.jconhyd.2009.12.003

Halvorson, A. D., Follett, R. F., Bartolo, M. E., & Schweissing, F. C. (2002). Nitrogen fertilizer use efficiency of furrow-irrigated onion and corn. *Agronomy Journal*, *94*(3), 442-449. https://doi.org/10.2134/agronj2002.4420

Hasegawa, H., & Denison, R. F. (2005). Model predictions of winter rainfall effects on N dynamics of winter wheat rotation following legume cover crop or fallow. *Field Crops Research*, *91*(2-3), 251-261. https://doi.org/10.1016/j.fcr.2004.07.019

Lancaster, J. E., & Boland, M. J. (1990). Flavor biochemistry, p 33-72. In: Brewster JL, Rabinowitch, HD (eds). *Onions and Allied Crops.* CRC Press, Boca Raton, FL.

McCallum, J., Porter, N., Searle, B., Shaw, M., Bettjeman, B., & McManus, M. (2005). Sulfur and nitrogen fertility affects flavour of field-grown onions. *Plant and Soil*, *269*, 151-158. https://doi.org/10.1007/s11104-004-0402-5

Randle, W. M. (2000). Increasing nitrogen concentration in hydroponic solutions affects onion flavor and bulb quality. *Journal of the American Society for Horticultural Science*, *125*(2), 254-259. https://doi.org/10.21273/JASHS.125.2.254

Sharma, P., Shukla, M. K., Sammis, T. W., & Adhikari, P. (2012). Nitrate-nitrogen leaching from onion bed under furrow and drip irrigation systems. *Applied and Environmental Soil Science*, *2012*. https://doi.org/10.1155/2012/650206

Sial, A., Johnson, A., & Cabrera, E. (2022). Georgia commercial pest management handbook volume I. *University of Georgia Cooperative Extension Bulletin* 28.

Strydom, E. (1964). A root study of onions in an irrigation trial. *South African Journal of Agricultural Science*, *7*(4), 593-601. https://hdl.handle.net/10520/AJA05858860_329

Stumpf, S., Leach, L., Srinivasan, R., Coolong, T., Gitaitis, R., & Dutta, B. (2021). Foliar chemical protection against Pantoea ananatis in onion is negated by thrips feeding. *Phytopathology*, *111*(2), 258-267. https://doi.org/10.1094/PHYTO-05-20-0163-R

Tekalign, T., Abdissa, Y., & Pant, L. M. (2012). Growth, bulb yield and quality of onion (Allium cepa L.) as influenced by nitrogen and phosphorus fertilization on vertisol. II: Bulb quality and storability. *African Journal of Agricultural Research*, *7*(45), 5980-5985. https://doi.org/10.5897/AJAR10.1024

University of Georgia. (2022). 2021 Georgia farm gate value report. *University of Georgia Cooperative Extension Bulletin* AR 22-01. https://caed.uga.edu/publications/farm-gate-value.html [accessed 25 May 2023].

US Department of Agriculture. (2022). National Agricultural Statistics Service. Quick Stats. *US Department of Agriculture*, Washington, DC. https://quickstats.nass.usda.gov/ [accessed 23 May 2023].

Wright, P. J. (1993). Effects of nitrogen fertilizer, plant maturity at lifting, and water during field-curing on the incidence of bacterial soft rot of onions in store. *New Zealand Journal of Crop and Horticultural Science*, *21*(4):377-381. https://doi.org/10.1080/01140671.1993.9513796

Zotarelli, L., Rens, L. R., Cantliffe, D. J., Stoffella, P. J., Gergela, D., & Burhans, D. (2015). Rate and timing of nitrogen fertilizer application on potato 'FL1867'. Part I: Plant nitrogen uptake and soil nitrogen availability. *Field Crops Research*, *183*, 246-256. https://doi.org/10.1016/j.fcr

CHAPTER 4

ESTIMATING FERTILIZER NITROGEN USE EFFICIENCY IN TRANSPLANTED SHORT-DAY ONION[2]

[2] de Jesus, H. I., da Silva, A. L. B. R., Cassity-Duffey, K., & Coolong, T. (2023). *Nitrogen*, *4*(3), 286-295. https://doi.org/10.3390/nitrogen4030021. Reprinted here with permission of the publisher.

Abstract

Efficient nitrogen (N) fertilizer applications in onion (*Allium cepa* L.) can reduce input costs and improve fertilizer use efficiency, while maintaining high yields and quality. Understanding the N requirements of onion at different growth stages is necessary to enhance fertilizer N use efficiency (FNUE). In a two-year study (2021 and 2022), the FNUE of onions was determined at five stages of development (at transplant, vegetative growth, bulb initiation, bulb swelling and bulb maturation). The FNUE was estimated by substituting a conventional N fertilizer (ammonium nitrate) with a 5% enriched ^{15}N ammonium nitrate at a rate of 22.4 $kg{\cdot}ha^{-1}$ N at one of five application times corresponding to a stage of development. All onions received a season total of 112 $kg{\cdot}ha^{-1}$ N. Marketable yield of onions was significantly greater in 2022 compared to 2021 and FNUE was affected by application timing in both years. In 2021, the FNUE at transplant was 8.87%, increasing to 26.38% and 35.28% at vegetative growth and bulb initiation stages, respectively. At bulb swelling and bulb maturation stages FNUE was greater than 95%. In 2022, the FNUE at transplant was 25.22%. This increased to 75.74% and 103.02% vegetative growth and bulb initiation stages, respectively. Results suggest that the application of fertilizer N at transplant is inefficient due to limited plant uptake ability, while N applications during bulb initiation and swelling were the most efficient.

Introduction

Nitrogen (N) is an essential nutrient for plants, as it plays a vital role in the synthesis of amino acids, proteins, and chlorophyll, and is often considered the most limiting element for growth of onion (*Allium cepa* L.) (Brewster, 2008). Most active roots in onion are found in the upper 15 cm soil depth while the maximum rooting depth is typically 30 cm (Strydom, 1964;

Ajdary et al., 2007; Machado et al., 2009). In addition to being shallow-rooted, onion roots typically are limited to a radius of 15-20 cm around each plant (de Melo, 2003). The limited root zone leads to a less efficient uptake of water and nutrients, especially in coarse textured soils with low water-holding capacity, such as the sandy loam soils of the Coastal plain southeastern Georgia, USA, where short-day onions are extensively cultivated. In these soils, N is vulnerable to leaching (Delgado, 2002), making N fertilizer management a continuing challenge for onion growers (Boyhan, 2008).

High rates of N fertilizers are usually applied to onion in the U.S. to increase the overall yields and bulb size (Brown, 1997; Boyhan, 2008; Boyhan et al., 2007). Commercially acceptable yields have been achieved in Georgia, USA through the application of 117 $kg \cdot ha^{-1}$ N (da Silva et al., 2022). While high yields of onions depend on soil N availability, excessive N fertilizer applications can have negative consequences such as N leaching, increased production cost, and reduced bulb quality (Greenwood et al., 1980; Sharma et al., 2012; Lee et al., 2014). Optimizing the fertilizer N use efficiency (FNUE) of onions may aid in reducing total N fertilizer application rates. Split applications of N fertilizers have been reported to be more effective for maintaining yields of onion crops than a single N application at planting (Batal et al., 1994; Biesiada & Kolota, 2009). Previous studies have reported that splitting total crop N fertilizer requirements into at least three applications throughout the growing season can enhance yields compared to fewer applications when onions are grown on coarse-textured soils (Boyhan et al., 2007; Boyhan & Kelley, 2008; da Silva et al., 2022). To maximize benefits from splitting N fertilizer applications, the timing of application should be synchronized with plant N demands at different stages of growth (da Silva et al., 2022). This ensures that soil N levels in the root zone do not exceed crop requirements, which may reduce the residence time of N in the soil and lower the risk of soil N leaching (Geisseler et al., 2022).

Currently, little information is available on the FNUE of short-day onions in humid subtropical climates such as found in Georgia, USA [Halvorson et a., 2002; Sharma et al., 2012). The objective of this study was to evaluate the FNUE of short-day onions across five distinct developmental stages to optimize the timing of fertilizer applications.

Materials and Methods

Field experiments were conducted during the 2021 and 2022 onion production seasons at the University of Georgia, Vidalia Onion and Vegetable Research Center located in Lyons, GA, USA (32°00'58'' N, 82°13'17'' W). The region is classified with a humid subtropical climate and soil characterized as an Irvington loamy sand, 2% slope (USDA, 2022). Preplant soil tests from the plot indicated that organic matter was approximately 0.6% with a pH range of 6.4 to 6.8. Onions had not been grown in the fields utilized for this for 2 years prior to planting. Cover crops, including cereal rye (*Secale cereale*) in winter and soybeans (*Glycine max*) in summer were grown on the land prior to onion crops. Fields were left fallow for several months prior to onion transplant.

Onion seedlings 'Vidora' (BASF-Nunhems Inc., Parma, ID, USA) were grown in nursery beds on the research site for approximately 8 weeks. Seedlings were removed from transplant beds by hand and foliage cut to a length of approximately 10 cm. Bareroot seedlings were then transplanted to the field on 10 Dec 2020 and 7 Dec 2021. Seedlings were transplanted into beds 15 cm tall and spaced 1.82 m center to center, with each bed having four rows of onions spaced approximately 25 cm apart with an in-row plant spacing of 10 cm, resulting in a plant population of 215,186 plants·ha^{-1}. Plots were 6 m long and separated by 3 m non-planted buffers between adjacent plots within a row. Each plot contained approximately 240 plants.

The stable isotope of N (^{15}N) was utilized to determine FNUE in the field. Five ^{15}N labeled fertilizer application treatments: at transplant, vegetative growth, bulb initiation, bulb swelling, and bulb maturation were evaluated in a randomized complete block design with four replications in both study years (Table 4.1). A ^{15}N labeled ammonium nitrate ($^{15}NH_4{}^{15}NO_3$) (Sigma Aldrich, St. Louis, MO, USA) was the N source used to determine the crop N uptake efficiency at each fertilizer application timing. The ^{15}N was applied in 1.5 m long sub-plots in the center of each plot at a rate of 22.4 kg·ha^{-1}. Plots receiving the ^{15}N fertilizer also received 22.4 kg·ha^{-1} N of unlabeled NH_4NO_3 in the other four application times for total application of 112 kg·ha^{-1} N. In each plot, the area adjacent to the ^{15}N subplots received unlabeled N in all application timings.

Table 4.1. Labeled nitrogen (N) application timings and rates.

Treatments	NT	NV	NBI	NBS	NBM	Total N
	N rate (kg·ha^{-1} N)					
^{15}NT	22.4[1]	22.4	22.4	22.4	22.4	112
^{15}NV	22.4	22.4	22.4	22.4	22.4	112
^{15}NBI	22.4	22.4	22.4	22.4	22.4	112
^{15}NBS	22.4	22.4	22.4	22.4	22.4	112
^{15}NBM	22.4	22.4	22.4	22.4	22.4	112

[1] The time ^{15}N fertilizer is being applied; NT = N applied at transplant; NV = N applied at vegetative stage; NBI = N applied at bulb initiation; NBS = N applied bulb swelling; NBM = N applied during maturation.

During each growing season, onions were overhead irrigated using stationary sprinklers. Irrigation water volume was determined according to onion evapotranspiration and precipitation. Air temperatures and rainfall were monitored and recorded every 15 min using an on-farm weather station from the Georgia Automated Environmental Monitoring Network (University of Georgia, 2022). Preemergent herbicides oxyfluorfen (0.56 kg·ha^{-1}) (Goal 2xL; NuFarm, Alsip, IL, USA) and pendimethalin (0.92 kg·ha^{-1}) (Prowl 3.3EC; BASF, Research Triangle Park, NC, USA) were broadcast applied over onion transplants within 7 days after transplant (DAT) in both study years. Routine fungicide and insecticide applications were made weekly during the season according to recommendations for the region (Sial et al., 2023).

Onions were harvested on 20 Apr 2021 (131 DAT) and 19 Apr 2022 (133 DAT) (Table 4.2). Bulbs were manually pulled from the soil to cure in the field for approximately 2 days, after which foliage and root tissue were manually cut and bulbs harvested. Harvested bulbs were cured using forced air-heat (35 °C) for 3 days and then graded into colossal (>9.5 cm diameter), jumbo (8.25 to 9.5 cm diameter), and medium (<8.25 cm diameter) sizes according to US Department of Agriculture (USDA) standards for Bermuda-Granex-Grano type onions (USDA, 2014).

Table 4.2. Time of labeled nitrogen (^{15}N) application and harvest in 2021 and 2022 in days after transplant (DAT).

Year	^{15}NT[i]	^{15}NV	^{15}NBI	^{15}NBS	^{15}NBM	Harvest
	Days after transplant (DAT)					
2021	5	27	49	78	99	131
2022	9	30	57	78	99	133

[1] The time ^{15}N fertilizer is being applied; NT = N applied at transplant; NV = N applied at vegetative stage; NBI = N applied at bulb initiation; NBS = N applied bulb swelling; NBM = N applied during maturation.

FNUE evaluation

The FNUE for each ^{15}N application was evaluated at harvest in the 1.5 m sub-sections of each plot, in which two onion plants from the center two rows were sampled to determine FNUE (Olson, 1980). Onion plants were separated into leaves, bulbs, and roots, and dried at 70 °C using a forced air oven to a constant weight, ground using a Wiley mill (Thomas Scientific, Swedesboro, NJ, USA), and sieved using a 20-mesh screen. Soil samples (comprised of 5 sub-samples within the center rows of each subplot) were collected at a depth of 15 cm using a soil probe (2.2 cm diameter, AMS, American Falls, ID, USA) to determine the remaining N in the soil derived from ^{15}N-isotope fertilizer at harvest.

Dry soil and plant tissue were once more ground in a ball mill to a fine powder and samples were submitted for total N and ^{15}N analyses at the University of California Davis Stable Isotope Facility (University of California, Davis, CA, USA). The plant N derived from ^{15}N labeled fertilizer (Ndff) in kg·ha^{-1} and N fertilizer uptake efficiency (FNUE) were calculated according to the International Atomic Energy Agency (IAEA, 1983), using the following equations:

$$\mathrm{Ndff} = \frac{\%\ ^{15}\mathrm{N\ atom\ excess\ of\ the\ plant\ sample}}{\%\ ^{15}\mathrm{N\ atom\ excess\ of\ the\ fertilizer\ applied}} * \mathrm{plant\ N\ uptake\ (kg \cdot ha^{-1})} \qquad (4.1)$$

where atom excess is the measured percentage above natural abundance of 0.3663% ^{15}N, and the ^{15}N atom excess of fertilizers provided by fertilizer manufacturer.

$$\mathrm{FNUE} = \frac{\mathrm{Ndff}}{\mathrm{applied\ N\ rate(kg \cdot ha^{-1})}} * 100 \qquad (4.2)$$

where the applied N rate at each application timing is 22.4 kg of N ha^{-1}.

$$\mathrm{NHI} = \frac{\mathrm{kg \cdot ha^{-1}\ of\ N\ in\ bulbs}}{\mathrm{kg \cdot ha^{-1}\ of\ N\ in\ whole\ plant}} \qquad (4.3)$$

Statistical analysis

Data were analyzed using the Linear Mixed Model from JMP Pro 16.0 (SAS Institute Inc., Cary, NC). The Ndff and FNUE were analyzed using time (stage of development) of fertilizer N application, year, and their interactions as fixed effects, while block was treated as a random effect.

When statistically significant differences existed in the ANOVA (P<0.05), Least-square means comparisons were performed using the Tukey's Honest Significant Difference test (α = 0.05).

Results

During the studies there were 531 and 426 mm of rainfall in 2020 and 2021, respectively (Figure 4.1). There were 160 and 145 mm of rainfall between onion transplant and vegetative growth stages (27 DAT and 30 DAT) in 2021 and 2022, respectively. In 2021, there were 242 mm of rainfall from early bulb initiation until the bulb swelling stage of growth (28-78 DAT), but this decreased to 100 mm from early bulb initiation until the bulb swelling stages of growth (31-78 DAT) in 2022. Between bulb swelling and harvest, there were 129 mm of rainfall in 2021 (79-131 DAT) and 181 mm in 2022 (79 – 133 DAT). Rainfall events exceeded onion evapotranspiration for both study years (da Silva et al., 2019).

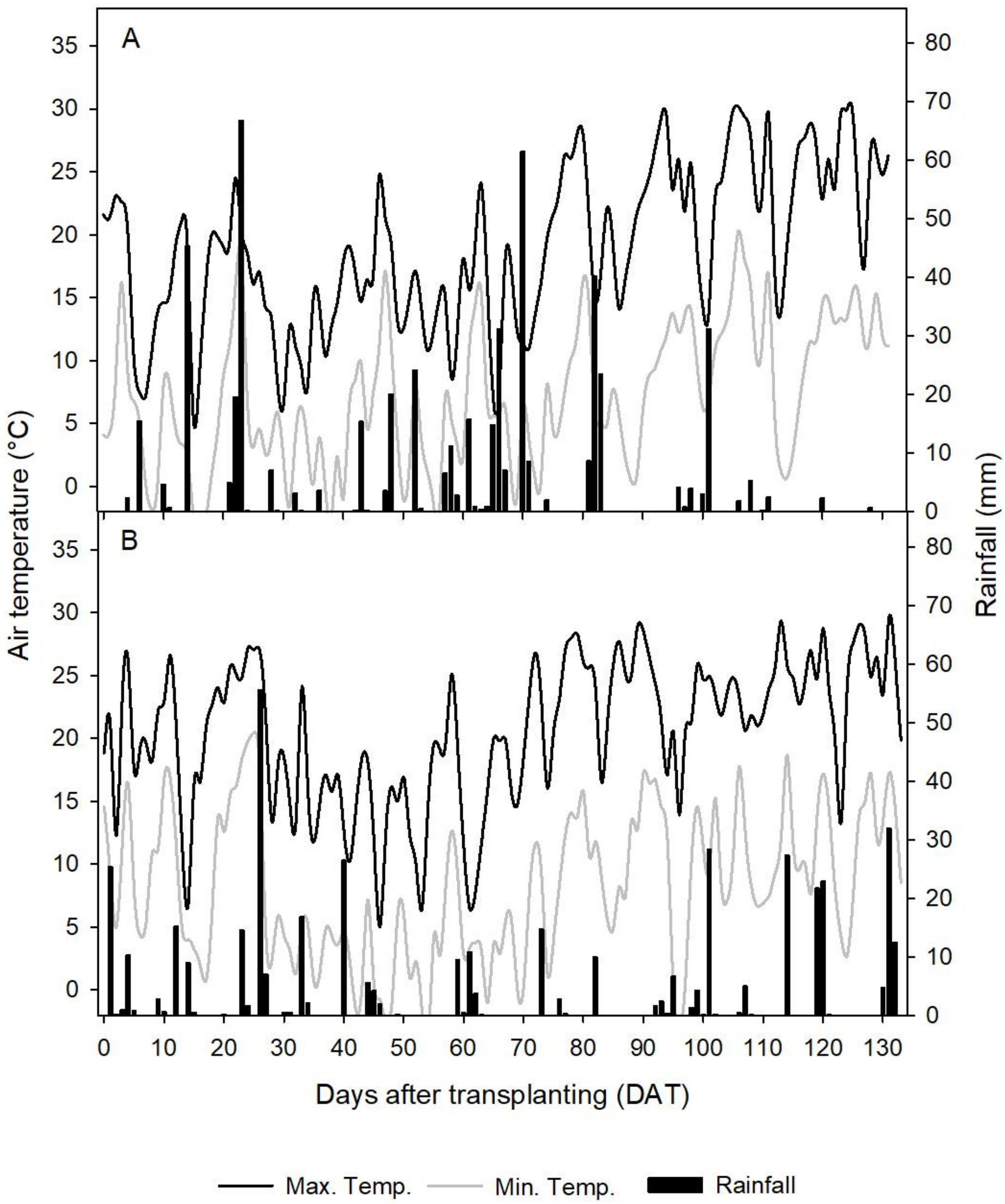

Figure 4.1. Daily maximum (max.) and minimum (min.) air temperatures (°C) and rainfall (mm) for onion (Allium cepa L.) grown during 2021 (A) and 2022 (B) in Georgia, USA. Data averages estimated using the University of Georgia Weather Network.

Total marketable yield of onions was 58 404 kg·ha^{-1} in 2022, compared to 49 360 kg·ha^{-1} in 2021 (Table 3). Yields of colossal bulbs were significantly greater in 2022 (10,272 kg·ha^{-1}) than in 2021 (81 kg·ha^{-1}). The yield of jumbo bulbs, which constitute the majority of harvested bulbs, was also greater in 2022 (46 053 kg·ha^{-1}) compared to 2021 (41 791 kg·ha^{-1}). In contrast, the yield of medium bulbs was greater in 2021 (7 487 kg·ha^{-1}) compared to 2022 (2 079 kg·ha^{-1}). Nitrogen harvest index was greater in 2022 (0.81) compared to 2021 (0.54) (Table 4.3).

Table 4.3. Marketable yield, bulb size distribution, percentage culls, and nitrogen harvest index (NHI) of onions (*Allium cepa* L.) harvested in 2021 and 2022.

Year	Marketable		Colossal		Jumbo		Medium		Culls		NHI	
	kg ha^{-1}										(%)	
2021	49 360	b [1]	81	b	41 791	b	7 487	a	2.69	b	0.54	a
2022	58 404	a	10 272	a	46 053	a	2 079	b	7.30	a	0.81	b

[1] Values followed by the same letters indicate no significant difference by the Tukey test ($p<0.05$).

There was a significant year by application time interaction for Ndff and FNUE (Table 4.4). In 2021, the Ndff in the whole plant and parts (bulbs, leaves, and roots) was significantly lower with ^{15}N applications at transplant, vegetative growth, and bulb initiation stages of development. In 2021 the majority of Ndff could be attributed to the two ^{15}N applications at bulb swelling and bulb maturation. In 2021 the total Ndff was similar between onion bulbs and leaves. In 2022, the lowest Ndff in the whole plant was associated with ^{15}N applications at transplant, while the greatest Ndff in the whole plant was associated with the ^{15}N applications at bulb initiation. Similar results were observed for Ndff in the bulbs; in contrast, the Ndff in the leaves was mainly from fertilizer N application at vegetative and bulb initiation stages. In 2022, the total accumulation of Ndff was higher in the bulbs compared to the leaves.

Table 4.4. Effects of labeled nitrogen (^{15}N) fertilizer application timing on nitrogen derived from fertilizer (Ndff) at onion bulbs, leaves, roots and total plant, and fertilizer nitrogen use efficiency (FNUE) measured at harvest.

Treatment	Bulbs	Leaves	Roots	Total plant	FNUE (%)

	Ndff (kg·ha^{-1} ^{15}N)									
2021										
^{15}NT [1]	1.16	c [2]	0.91	d	0.02	c	2.09	c	8.9	c
^{15}NV	3.37	bc	2.80	c	0.04	bc	6.21	b	26.4	b
^{15}NBI	4.67	b	3.59	c	0.05	bc	8.30	b	35.3	b
^{15}NBS	11.75	a	12.93	a	0.08	a	24.76	a	105.2	a
^{15}NBM	12.76	a	10.00	b	0.05	ab	22.81	a	96.9	a
Total ^{15}N	33.70		30.22		0.24		64.16			
HSD [3]	2.30		1.49		0.03		2.96		12.60	
2022										
^{15}NT	4.62	b	1.28	b	0.04	a	5.94	b	25.2	b
^{15}NV	14.16	ab	3.57	a	0.10	a	17.83	ab	75.7	ab
^{15}NBI	20.22	a	3.95	a	0.08	a	24.25	a	103.0	a
^{15}NBS	15.38	ab	2.84	ab	0.06	a	18.28	ab	77.6	ab
^{15}NBM	10.97	ab	1.54	b	0.05	a	12.56	ab	53.3	ab
Total ^{15}N	65.35		13.18		0.33		78.85			
HSD	12.22		1.90		0.08		13.56		57.64	

[1] The time ^{15}N fertilizer is being applied; NT = N applied at transplant; NV = N applied at vegetative stage; NBI = N applied at bulb initiation; NBS = N applied bulb swelling; NBM = N applied during maturation.
[2] Values followed by the same letters indicate no significant difference by the Tukey test ($p<0.05$) among N fertilizer timing treatments within a year.
[3] HSD = Honest Significant Difference (minimum significant difference) according to the Tukey test ($p<0.05$).

The average Ndff in the soil, which is a measurement of the ^{15}N remaining in the soil at harvest, was 3.27 kg·ha^{-1} in 2021, which was significantly lower than the 4.03 kg·ha^{-1} of Ndff in the soil in 2022 (Table 4.5).

Table 4.5. Nitrogen (N) derived from ^{15}N labeled isotope fertilizer that was determined in the soil at harvest in 2021 and 2022.

Year	Ndff in Soil (kg·ha^{-1} ^{15}N)	
2021	3.27	b [1]
2022	4.03	a

[1] Values followed by the same letters indicate no significant difference by the Tukey test ($p<0.05$).

In 2021, the FNUE at transplant, vegetative growth and bulb initiation was 8.9%, 26.4%, and 35.3% respectively. At bulb swelling and bulb maturation, the FNUE was significantly higher than the previous application timing, with 105.2% and 96.9% of N fertilizer applied, respectively, being taken by the plant. In 2022, the labeled ^{15}N application at transplant had the lowest FNUE (25.2%). The FNUE increased to 75.7% when applied during the vegetative growth phase of development. The highest FNUE in 2022 was when ^{15}N was applied during bulb initiation (103.0%). The FNUE at bulb swelling and bulb maturation in 2022 was 77.6% and 53.3%, respectively.

Discussion

Recommended N application rates for onion production in the Coastal Plain region of Georgia, USA, range between 125 to 150 $kg \cdot ha^{-1}$ N (Coolong et al., 2017). However, da Silva et al. (2022) reported that applying 117 $kg \cdot ha^{-1}$ N in Georgia, USA could maintain soil N availability throughout the season and sustain commercially acceptable onion yields. In this study, we applied 112 $kg \cdot ha^{-1}$ N split into five applications throughout the onion growing season and achieved commercially acceptable yields (Coolong et al., 2017). Marketable yields were greater in 2022 compared to 2021, with most of the increase in yield resulting from an increase in colossal-sized bulbs in 2022.

In 2021, ^{15}N applications at transplant, vegetative growth, and bulb initiation had a lower FNUE than comparable application times in 2022. Frequent rainfall events in 2021, particularly from 0 to 75 DAT, may have induced N leaching, reducing soil N availability in the first half of the season. A reduction in soil N availability may have also resulted in lower N recovery in the whole plant in 2021 (Figure 4.1, Table 4.4). In contrast, rainfall amounts were lower and more evenly distributed during the growing season in 2022, resulting in a greater FNUE for the first three ^{15}N applications (transplant, vegetative growth, and bulb initiation) compared to the same application times in 2021. In 2021 highest FNUE occurred at bulb swelling (78 DAT) and bulb maturation (99 DAT), while in 2022 the greatest FNUE was from the ^{15}N application at bulb initiation (57 DAT). In both years the ^{15}N applications at transplant had the lowest FNUE, which can be, in part, due to the low N requirements by onion plants at this developmental stage. As a result, residence time of N fertilizer in the soil may increase, enhancing the chances of soil N leaching caused by the frequent rainfall during the production season.

Nitrogen uptake follows a sigmoidal curve in onion (Geisseler et al., 2022). Minimal N accumulation occurs in the aboveground biomass early in the season, increasing as the season progresses and the bulbs begin to develop. This leads to rapid N uptake during bulb development and maturation, slowing down in the final weeks before harvest (Geisseler et al., 2022). Growers in the Georgia, USA typically make their first N applications at or immediately after transplant to ensure fertilizer is available at plant establishment (Tyson C, personal communication). However, the low FNUE from at-transplant N applications in 2021 and 2022 suggests that N applications are higher than crop requirements at this stage of development (Table 4.4).

Nitrogen is required to in the greatest abundance of all plant nutrients for a myriad of cellular processes in the plant. Root architecture and the genes controlling root growth may limit N uptake in onion seedlings (Xu et al., 2012). Even if abundant N is available in the soil solution, plants may limit N uptake to maintain cytosolic pH balance and cellular homeostasis (Xu et al., 2012). Foliar N concentrations peak early in onion development at values approaching 4% on a dry weight basis, and then decline as aboveground biomass increases (Greenwood & Draycott, 1989). This is due to the relative decline in leaf area relative to overall biomass of plants and is termed the critical N dilution curve (Lemaire et al., 2008). While overall total N content in the plant increases during growth as crop biomass increases, the relative concentration of N in continues to decline. Thus, when N availability in the soil is not limited, N removal from the soil and accumulation in the plant early in onion development would be limited by a lack of plant biomass compared to later growth stages. Given the limited ability to scavenge N from the soil due to a small root biomass and overall low biomass of onion at transplant it would be expected to accumulate relatively little of the applied ^{15}N during this stage of development. Due to the highly leachable nature of the sandy soils in the region (Delgado, 2002) and rainfall that occurred within 30 DAT (Figure 4.1) it is unlikely that N applied at transplant would remain in the rootzone for acquisition later in the season when biomass increases would allow for further ^{15}N accumulation by the plant.

In 2022 the application of N during vegetative growth resulted in a FNUE of 75.7%, which was greater than the FNUE of 26.4% in 2021 for same stage of development. Maximum air temperatures were greater in 2022 than 2021 during the vegetative growth phase, which may have resulted in improved plant growth and a subsequently larger FNUE. During vegetative growth and bulb initiation, adequate N supply is necessary to ensure sufficient foliar growth that will support production of larger bulbs during the bulb swelling and maturation stages of development. In addition to lower daily maximum temperatures after transplant in 2021, there were multiple rain events that occurred shortly after the ^{15}N applications at bulb initiation, which may have also reduced the N availability from the fertilizer applied at this stage. The lower FNUE at bulb initiation in 2021 may have resulted in less leaf biomass prior to bulbing, potentially reducing yields.

Nitrogen concentrations in leaf tissue above which are necessary to maximize yield are often termed luxury consumption. In onion, luxury consumption of N is generally low (Greenwood et al., 1980). This suggests that the higher values for FNUE during vegetative growth and bulbing were due to utilization of N in the plant and not due to luxury consumption of N.

The primary sink for N in onion plants at maturity are the bulbs (Brewster, 2008). However, a larger proportion of Ndff was allocated in the leaf tissue in 2021 compared to 2022. It has been reported that approximately 65% of above-ground N is found in bulbs at harvest, while the remaining 35% is found in leaves (Geisseler et al., 2022). In 2021, relatively similar amounts of Ndff were found in bulb and leaf tissue at harvest. In contrast, in 2022 most Ndff accumulated in the bulb tissue. Accordingly, NHI was significantly higher in 2022 compared to 2021. The continued accumulation of Ndff in the leaf tissue in 2021 during bulb swelling and maturation compared to 2022 may have been associated with an extended period of vegetative growth in 2021 (Geisseler et al., 2022). A relative increase in bulb size in 2022 (Table 4.3) may have also increased bulb Ndff. In addition, there was an increase in variability in Ndff in 2022 compared to 2021, particularly in bulb and total plant Ndff values. An increase in the proportion of colossal-sized bulbs in 2022 may have led to greater variability in plant biomass when sampling at harvest, resulting in increased variation in Ndff values in 2022.

The greater relative accumulation of Ndff in bulb tissue in 2022 beginning at bulb initiation may have resulted in greater allocation of resources in the bulb and greater yields. Delaying N applications until bulb maturation has been shown to negatively impact yield, compared to applications at bulb initiation or bulb swelling (Tyson et al., 2023). Because onion cultivars may differ widely in days to maturity, recommendations for onion N applications are made at a regional level, considering the time of year the crop is grown, days to harvest, whether onions are direct seeded or transplanted, and fertilizer source used (Drost, 2002; Geisseler et al., 2022). Onion cultivars vary in daily N uptake as well, with earlier maturing varieties accumulating significantly more N than later maturing onions. In the current study a short-day onion 'Vidora' was used, which was harvested approximately 130 DAT. While our data suggests that N applications in this study were most efficient when coinciding with periods later in plant development such as during bulb initiation, earlier maturing varieties may incorporate N fertilizers earlier in crop development. Although fertilizer N applications during bulb maturation may result in high FNUE, they can also lead to reduced quality and storage life in bulbs (Randle, 2000). Interestingly, a season total N application of 112 $kg \cdot ha^{-1}$ N, which was the N application rate utilized in the current study, was reported to have a higher nitrogen use efficiency when compared to applications of 168 and 224 $kg \cdot ha^{-1}$ N in an evaluation comparing different sources and rates of N fertilizers (Drost, 2002). Increased applications of N above those used in the present study, particularly late in the season, may reduce the FNUE during bulbing relative to growth stages earlier in the season.

Conclusions

This study aimed to assess the FNUE of N fertilizer applied during five different stages of development of onion. The application of N at transplant was inefficient as only a limited portion of what is applied was taken up by the plant. Nitrogen applications during bulb initiation and bulb swelling were generally the most efficient stages of development to apply N fertilizer in onion.

Literature Cited

Ajdary, K., Singh, D. K., Singh, A. K., & Khanna, M. (2007). Modelling of nitrogen leaching from experimental onion field under drip fertigation. *Agricultural water management, 89*(1-2), 15-28. https://doi.org/10.1016/j.agwat.2006.12.014

Batal, K. M., Bondari, K., Granberry, D. M., & Mullinix, B. G. (1994). Effects of source, rate, and frequency of N application on yield, marketable grades and rot incidence of sweet onion (Allium cepa L. cv. Granex-33). *Journal of Horticultural Science*, *69*(6), 1043-1051. https://doi.org/10.1080/00221589.1994.11516543

Boyhan, G. E., & Kelley, W. T. (2008). Onion production guide. *University of Georgia Cooperative Extension Bulletin* 1198.

Boyhan, G. E., Torrance, R. L., & Hill, C. R. (2007). Effects of nitrogen, phosphorus, and potassium rates and fertilizer sources on yield and leaf nutrient status of short-day onions. *HortScience*, *42*, 653–660. https://doi.org/10.21273/HORTSCI.42.3.653.

Biesiada, A., & Kołota, E. (2009). The effect of nitrogen fertilization on yield and nutritional value of onion grown from sets for early cropping. *Journal of Fruit and Ornamental Plant Research*, *70*(1), 145-151. https://doi.org/10.2478/v10032-009-0014-y

Brewster, J. L. (2008). Onions and other vegetable alliums (2nd edition). CABI, Wellesbourne, UK.

Brown, B. (1997). Soil test N for predicting onion N requirements—An Idaho perspective. In *Proceedings of the Western Nutrient Management Conference* (pp. 43-48). Salt Lake City, UT.

Coolong, T., & Boyhan, G. (2017). Onion production guide. *University of Georgia Cooperative Extension Bulletin* 1198.

da Silva, A. L. B. R., Coolong, T., & Smith, E. Irrigating. (2019). *University of Georgia*. Available online: https://irrigating.uga.edu/ (accessed 22 Apr 2023).

da Silva, A. L. B. R., Rodrigues, C., Dunn, L., Cavender, G., & Coolong, T. (2022). Fertilizer Nitrogen Application for Short-Day Onion Production: From Field to Table. *Horticulturae*, *8*, 847. https://doi.org/10.3390/horticulturae8090847.

Delgado, J. A. (2002). Quantifying the loss mechanisms of nitrogen. *Journal of Soil and Water Conservation*, *57*(6), 389-398.

de Melo, P.E. (2003). The Root Systems of Onion and *Allium Fistulosum* in the Context of Organic Farming: A Breeding Approach. Ph.D. thesis, Wageningen University and Research Centre, The Netherlands.

Drost, D., Koenig, R., & Tindall, T. (2022). Nitrogen use efficiency and onion yield increased with a polymer-coated nitrogen source. *HortScience*, *37*(2):338-342. https://doi.org/10.21273/HORTSCI.37.2.338.

Geisseler, D., Ortiz, R. S., & Diaz, J. (2022). Nitrogen nutrition and fertilization of onions (Allium cepa L.)–A literature review. *Scientia Horticulturae*, *291*, 110591. https://doi.org/10.1016/j.scienta.2021.110591

Greenwood, D. J., Cleaver, T. J., Turner, M. K., Hunt, J., Niendorf, K. B., & Loquens, S. M. H. (1980). Comparison of the effects of nitrogen fertilizer on the yield, nitrogen content and quality of 21 different vegetable and agricultural crops. *The Journal of Agricultural Science*, *95*(2), 471-485. https://doi.org/10.1017/S0021859600039514

Greenwood, D. J., & Draycott, A. N. N. (1988). Experimental validation of an N-response model for widely different crops. *Fertilizer Research*, *18*, 153-174. https://doi.org/10.1007/BF01049511

Halvorson, A. D., Follett, R. F., Bartolo, M. E., & Schweissing, F. C. (2002). Nitrogen fertilizer use efficiency of furrow-irrigated onion and corn. *Agronomy Journal*, *94*(3), 442-449. https://doi.org/10.2134/agronj2002.4420

International Atomic Energy Agency. (1983). A guide to the use of nitrogen-15 and radioisotopes in studies of plant nutrition: calculations and interpretation of data. IAEA, Vienna.

Lee, J., Hwang, S., Lee, S., Ha, I., Hwang, H., Lee, S., & Kim, J. (214). Comparison study on soil physical and chemical properties, plant growth, yield, and nutrient uptakes in bulb onion from organic and conventional systems. *HortScience*, *49*, 1563–1567. https://doi.org/10.21273/HORTSCI.49.12.1563

Lemaire, G., Jeuffroy, M. H., & Gastal, F. (2008). Diagnosis tool for plant and crop N status in vegetative stage: Theory and practices for crop N management. *European Journal of agronomy*, *28*(4), 614-624. https://doi.org/10.1016/j.eja.2008.01.005

Machado, R. M. A., Shahidian, S., Pivetta, C. R., & Oliveira, M. (2009). Nitrogen fertilization effects on rooting pattern and yield of intermediate-day onions bulb in Alentejo region. *Revista de Ciências Agrárias*, *32*, 113-122. https://doi.org/10.19084/rca.15731

Olson, R. V. (1980). Plot size requirements for measuring residual fertilizer nitrogen and nitrogen uptake by corn. *Soil Science Society of America Journal*, *44*(2), 428-429. https://doi.org/10.2136/sssaj1980.03615995004400020045x

Strydom, E. (1964). A root study of onions in an irrigation trial. *South African Journal of Agricultural Science*, *7*(4), 593-601. https://doi.org/10.10520/AJA05858860_329

Sharma, P., Shukla, M. K., Sammis, T. W., & Adhikari, P. (2012). Nitrate-nitrogen leaching from onion bed under furrow and drip irrigation systems. *Applied and Environmental Soil Science, 2012*. https://doi.org/10.1155/2012/650206

Sial, A., Johnson, A., & Cabrera, E. (2023). 2023 Georgia pest management handbook. *University of Georgia Cooperative Extension Bulletin* 28.

University of Georgia. (2022). Vidalia Georgia climate data. Available online: http://www.georgiaweather.net/. (accessed 20 Apr 2023).

US Department of Agriculture. (2014). United states standards for grades of Bermuda-Granex-Grano type onions. *US Department of Agriculture*, Washington, DC.

US Department of Agriculture. (2022). Soil survey. Web soil survey – Soil survey of Toombs County, Georgia. *US Department of Agriculture.* Available online: https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx (accessed 22 May 2023).

Tyson, C., Jackson, D., da Silva, A. L. B. R., Edenfield, J., Shirly, A., Bowen, D., Thigpen, D., Clark, D., Powell, S., Tanner, S., & Greene S. (2023). Irrigation and nitrogen fertilizer strategies for Vidalia onion production. In 2022 Vidalia Onion Extension and Research Report. *University of Georgia Cooperative Extension Bulletin* AP114-1. Available online: https://site.extension.uga.edu/vidaliaonion/2023/04/2022-vidalia-onion-research-extension-report/ (accessed 17 May 2023).

Xu, G., Fan, X., & Miller, A. J. (2012). Plant nitrogen assimilation and use efficiency. *Annual review of plant biology*, *63*, 153-182. 10.1146/annurev-arplant-042811-105532

CHAPTER 5

INFLUENCE OF ORGANIC FERTILIZER SOURCES AND APPLICATION RATES ON ONION PRODUCTION IN GEORGIA, USA[3]

---

[3] de Jesus, H. I., da Silva, A. L. B. R., Dutta, B., Cassity-Duffey, K., & Coolong, T. (2023). *HortTechnology*, *33*(4), 398-406. https://doi.org/10.21273/HORTTECH05254-23. Reprinted here with permission of the publisher.

Abstract

A range of organic fertilizers are available for vegetable crops; however, there is a lack of information regarding the performance and rates of organic fertilizers commonly used in the production of Vidalia onion (*Allium cepa*). Two commercial organic fertilizers, a mixed source organic fertilizer [MIX (10N-0.88P-6.6K)] and a pelleted poultry litter (PPL) (5N-1.8P-2.5K) were evaluated in two soil types at application rates of 0, 100, 150, 200, 250 and 300 lb/acre nitrogen (N). The aim was to determine their impact in the production of Vidalia onions in Georgia, USA with the objective of determining an optimal fertilizer source and application rate. Field trials were conducted in the 2019-20 and 2020-21 growing seasons in Watkinsville GA, USA (Cecil series sandy clay loam soil) and Tifton GA, USA (Tifton series loamy sand soil) on certified organic land. There were significant interactions between location, year, and fertilizer application rate for total marketable yield. In Watkinsville, total marketable yields of onions at different N rates ranged between 1320-4565 lb/acre in 2019-20, and between 9951-28,749 lb/acre in 2020-21. In Tifton, total marketable yields ranged from 3776-9264 lb/acre and 7094-14,066 lb/acre in the 2019-20 and 2020-21 seasons, respectively. Aboveground onion N accumulation at harvest was affected by an interaction among location, study year, and fertilizer rate. The largest plant N accumulation was in Watkinsville in 2020-21, ranging from 26 to 50.8 lb/acre N in the 0 and 300 lb/acre N treatments, respectively. In 2020, there were no differences in soil inorganic N at harvest between plots receiving the MIX (9 lb/acre N) or PPL (9.8 lb/acre N) in either location. In 2021, soil inorganic N was greater in plots receiving the MIX fertilizer (14.8 lb/acre N) compared to the PPL fertilizer (11.2 lb/acre N). Yields increased linearly with additional fertilizer therefore an optimum application rate for organic fertilizers was not determined.

Introduction

Vidalia sweet onions (*Allium cepa*) are an important crop for southeastern Georgia, USA. In 2021, there were over 11,000 acres of onions grown with a farm gate value of $168 million, making them one of the top vegetable crops for the state (University of Georgia, 2022a). Organic onion production represents roughly 7% of the total acreage of Vidalia onions, with approximately 793 acres of certified organic onion production reported by the US Department of Agriculture (USDA) in 2019 (USDA, 2019). This represents a value of more than $12 million, which continues to increase annually.

Recommendations for nitrogen (N) applications for conventional onion production in the Coastal Plain region of Georgia, USA, suggest the application of 100 to 130 lb/acre N (Coolong & Boyhan, 2017). However, growers in the region have been able to achieve similar yields with reduced fertilizer N rates through the careful timing of applications (Tyson C, personal communication). Research conducted in Georgia during in the 2020-21 onion season reported average marketable yields of 38,700 lb/acre for conventionally grown onions with the application of 92 lb/acre N, indicating the potential for reducing N fertilizer rates while maintaining yields (Tyson et al., 2023). In organic vegetable production systems, the efficient application of fertilizers can be challenging because there is a lack of knowledge regarding the rate of N mineralization and plant availability of other nutrients in many organic products. The release of mineral N from organic fertilizers varies depending on the source material, soil characteristics, and environmental conditions (Calderón et al., 2005; Cassity-Duffey et al., 2018; Reganold & Wachter, 2016). Failure to coordinate timing of N release from organic fertilizers with plant demand has the potential to reduce yields (Berry et al., 2002). Consequently, organic onion growers often over apply fertilizers to ensure adequate levels of plant-available N during the entire growing season (Boyhan et al., 2007). However, over application of fertilizers can negatively impact flavor and storage quality of onion, particularly if there are high levels of available N at harvest (Coolong & Randle, 2003; Díaz-Pérez et al., 2003; Gitaitis et al., 2008).

Organic onion growers in Georgia, USA typically use either fresh, non-composted poultry litter (PL) (applied in advance of planting) or pelletized poultry litter (PPL) products as their primary nutrient source. Georgia is a leading poultry (broiler) producing state (USDA, National Agricultural Statistics Service, 2022). There are approximately 2 million pounds of PL, a mixture of feces, feathers, wasted feed, and bedding materials, produced annually and available for application to agricultural lands (Dunkley et al., 2011). Total N content of PL ranges from 2% to 4%, though only a portion of this will become available to plants during the subsequent cropping season. Poultry litter is also a significant source of phosphorus (P) and contains all other essential nutrients for plants (Chastain et al., 2001; Evers, 1998). While PL is a readily available fertilizer for organic onion production in Georgia; there are some drawbacks associated with its use, including high salinity levels that can reduce plant growth, and environmental concerns due to the potential for pollution when PL is over-applied (Li-Xian et al., 2007; Sharpley, 1997). Additionally, the risk of foodborne illnesses from PL is a concern in the production of vegetable crops. Onions, which grow partially within the soil, may be at high risk of contamination for foodborne pathogens (US Food and Drug Administration, 2020; Islam et al., 2005).

In addition to PL, there are many commercial fertilizers available for certified organic vegetable production. These products are typically made from plant or animal byproducts that have been processed or composted for use in agriculture (Cassity-Duffey et al., 2020a). The N concentration of commercial organic fertilizers can vary widely with composition. Total N concentrations may range from 3% in alfalfa (*Medicago sativa*) meal to 13% and 15% in feather and blood meals, respectively (Cassity-Duffey et al., 2020a; Gale et al., 2006). Some fertilizers, such as blood meal and feather meal, release N relatively quickly, while others such as alfalfa meal, are reported to be slower-release sources of N (Agehara & Warncke, 2005; Hartz & Johnstone, 2006; Gale et al., 2006). The pool of potentially mineralizable N can widely vary depending on the product type, but N mineralization rates are generally greater and more consistent for commercial organic fertilizers than for PL and composts (Cassity-Duffey et al., 2020a).

The impact of some organic fertilizer sources on Vidalia onion production has been previously evaluated (Boyhan et al., 2010; Díaz-Pérez et al., 2018a, 2018b, 2021). Boyhan et al. (2010) reported no difference between two commercial organic fertilizers on yield of onion when fertilizers were applied at 150 lb/acre N. Díaz-Pérez et al. (2018a) reported a quadratic response of onion plant growth to application rates of organic fertilizer, with plant dry weights plateauing between 180 and 240 $kg \cdot ha^{-1}$ N using a PPL fertilizer. In the same study Díaz-Pérez et al. (2018b) reported a quadratic response of bulb yield to organic fertilizer rate, though yield continued to increase with increasing N rate. Despite prior research, information regarding the performance of different organic fertilizers applied over a range of application rates for the production of organic onions is limited. Thus, the objective of this study was to compare the impact of a mixed source organic fertilizer (MIX) and a pelleted poultry litter (PPL) product applied at multiple application rates in two soil types on Vidalia onion production.

Materials & Methods

Field experiments were conducted in Fall 2019 through Spring 2021 at the University of Georgia (UGA) Durham Horticulture Farm in Watkinsville, GA, USA (lat. 33º 5'N, long. 83º 3'W) and the UGA Horticulture Farm in Tifton, GA, USA (lat. 31º 5'N, long. 83º 5'W). The soil of the Watkinsville, GA, USA location is a Cecil sandy clay loam series (0% to 2% slope) while the Tifton, GA, USA location had a Tifton loamy sand series (USDA, 2022). Prior to planting, average soil total N, organic matter and pH were 0.21%, 1.80% and 6.1, respectively for the Tifton location and 0.31%, 3.10% and 6.0, respectively, for the Watkinsville location (UGA Agriculture Environmental Services Laboratories, Athens, GA, USA). In the Watkinsville location, average preplant P (67 lb/acre) and potassium (K) levels (223 lb/acre) were considered high and high, respectively. In the Tifton location, average preplant P (79 lb/acre) and K (76 lb/acre) were considered high and medium, respectively (UGA, 2020).

Plots were chisel plowed and harrowed prior to transplanting to a depth of approximately 8 inches. After initial tillage and 2 d prior to planting, fertilizers were applied to plant beds that were approximately 2-3 inches tall and spaced 6 ft center to center. Two commercial fertilizers, a MIX [10N-0.88P-6.6K (All Season Organic Fertilizer; Nature Safe, Irving, TX, USA)] composed of feather-meat-bone-blood meal, and a PPL [5N-1.8P-2.5K (Harmony Organic Fertilizer; Environmental Products LLC, Roanoke, VA, USA)] were applied to plots by hand at the rates of 0, 100, 150, 200, 250 and 300 lb/acre N.

The MIX fertilizer contained 9.44% total N with 0.49% inorganic N, while the PPL fertilizer contained 4.36% total N with 1.04% inorganic N (Table 5.1). Ammonium levels were 0.14% in both fertilizers, while nitrate levels were 0.9% and 0.35% in the PPL and MIX fertilizers, respectively (Waters Agricultural Laboratories, Camilla, GA, USA). No additional fertilizer was applied during the onion growing season. Due to the nature of the organic fertilizers, levels of P and K were not balanced between the different application rates of the PPL and MIX fertilizers. Pre-plant P and K levels were either at high or medium levels for both locations.

Table 5.1. Total nitrogen (N), ammonium (NH_4-N), nitrate (NO_3-N), total inorganic N, total carbon (C), and carbon-to-nitrogen (C/N) ratio of pelleted poultry [PPL (5N-1.8P-2.5K)] and mixed-source organic [MIX (10N-0.88P-6.6K)] fertilizers used to grow organic onions (*Allium cepa*).

Fertilizer	Total N	NO_3-N	NH_4-N	Total Inorganic N	Total C	C/N ratio
	% DW					
PPL	4.36	0.9	0.14	1.04	27.74	6.36
MIX	9.44	0.35	0.14	0.49	34.35	3.64

Fertilizer treatments were arranged in a randomized complete block design with four replications. Experimental units were 20 ft long and were separated by 10-ft non-planted buffers between adjacent plots within a bed. After application, fertilizers were incorporated to a depth of 6 inches using a tractor-mounted tiller. A planting wheel was used to make holes for onion plants on each bed. Beds received four onion rows spaced 12 inches apart with an in-row spacing of 6 inches, resulting in a population of 58,000 plants/acre.

Onion transplants of cultivar ‘Granex Yellow PRR’ (Seminis, St. Louis, MO, USA) were grown on a commercial certified organic farm for 8 weeks prior to planting. Onions were transplanted on 4 Dec 2019 and 2020 in the Watkinsville, GA location, and 4 Dec 2019 and 3 Dec 2020 in the Tifton, GA location. During the growing season, onions were overhead irrigated using sprinklers. Irrigation water volume was determined according to historical onion evapotranspiration and precipitation. Air temperatures and rainfall were monitored and recorded every 15 min using on-farm weather stations from the UGA weather network in each location (UGA, 2022b). Weeds were controlled within plots using a tractor-mounted tine weeder (Aerostar-

Classic 150; Einbock, Dorf an der Pram, Austria) in Watkinsville and hand cultivation in Tifton. No fungicide or insecticide applications were made during any growing season.

Soil samples (each comprised of five sub-samples) were collected from each plot at transplant and at harvest in both locations. After sampling, soil was air dried and tested for soil inorganic N content [ammonium (NH_4^+) and nitrate (NO_3^-)] at a commercial laboratory (Waters Agricultural Laboratories). In 2020, onion shoot, and bulb samples were collected at transplant and harvest for biomass estimation and N accumulation in each location. In 2021, plant samples were collected five times throughout onion growing season to monitor biomass and N uptake in each location. Samples consisted of two plants dried at 70 °C until a constant weight. Onion shoot, and bulb dry weight were determined, and samples were ground and analyzed for plant total N content at a commercial laboratory (Waters Agricultural Laboratories). Aboveground N accumulation was calculated as the dry weight of plants multiplied by the tissue N concentration expressed in a percentage. Nitrogen uptake efficiency at harvest (NUPE) was calculated by the following equation: NUPE = total N taken up by the plant / total N applied (Drost et al., 2002).

Onion plants were harvested on 1 May 2020 and on 7 May 2021 in Watkinsville, GA, and on 1 May 2020 and 3 May 2021 in Tifton, GA. Onions were hand-harvested, roots and tops were manually cut, and bulbs were left in the field for 48 h for curing. Bulbs were hand-graded by size and appearance as marketable and unmarketable according to USDA standards (USDA, 2014). Subsamples of 20 marketable bulbs were cut in a longitudinal orientation and the number of bulbs with internal visual symptoms of sour skin (*Pseudomonas cepacia*) and center rot (*Pantoea* spp.) recorded.

Total yield (pounds per acre), soil inorganic N at harvest (pounds per acre N), plant N accumulation at harvest (pounds per acre N), plant N uptake during the season (pounds per acre

N), NUPE (%) were analyzed using the Linear Mixed Model and Regression procedures from JMP Pro (var. 16.0; SAS Institute Inc., Cary, NC, USA). Year, location, organic fertilizer, N rate, and their interactions were analyzed as main factors, while block was considered a random effect. When statistically significant differences existed in the ANOVA (P<0.05), least-square means comparisons were performed using the Tukey's honest significant difference test (α = 0.05). In 2019-20 four plots were removed from the statistical analysis due to poor plant survival.

Results & Discussion

In 2019-20, cumulative rainfall was 38.5 inches in Watkinsville (Fig. 5.1A) and 24.7 inches in Tifton (Fig. 5 2A). In the 2020-21 season, rainfall totaled 21.0 inches (Fig. 5.1B) and 32.0 inches in the Watkinsville and Tifton locations, respectively (Fig. 5.2B). Multiple rain events of more than 2.0 inches were common in the Watkinsville location in the 2019-20 growing season and a single rainfall event of 6.4 inches occurred approximately 1 week prior to harvest in Tifton for the 2020-21 growing season.

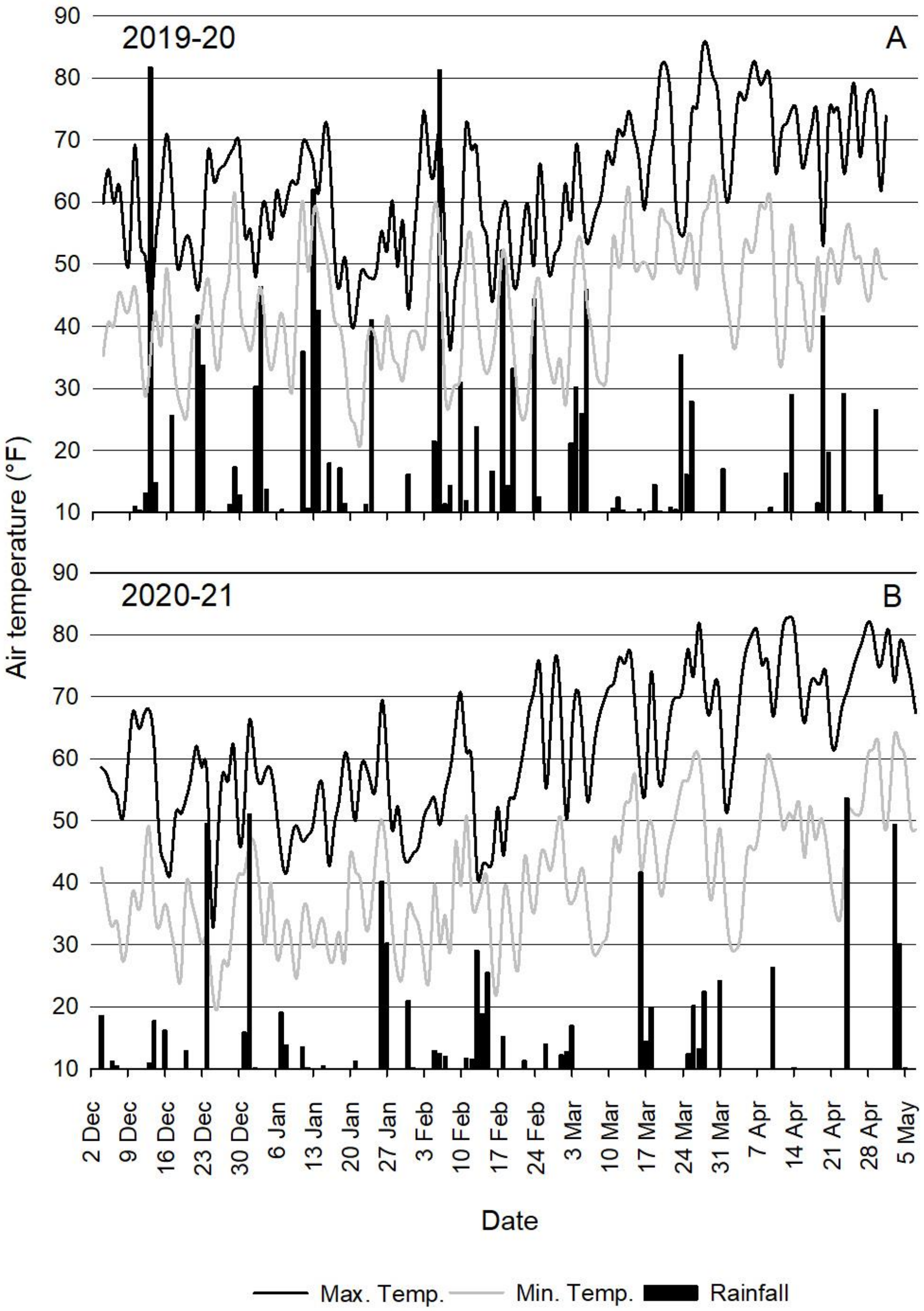

Fig. 5.4. Average daily maximum and minimum air temperatures and accumulated rainfall for the 2019-20 (A) and 2020-21 (B) season for onion (*Allium cepa*) grown in Watkinsville, GA, USA; (ºF - 32) ÷ 1.8 = ºC, 1 inch = 2.54 cm.

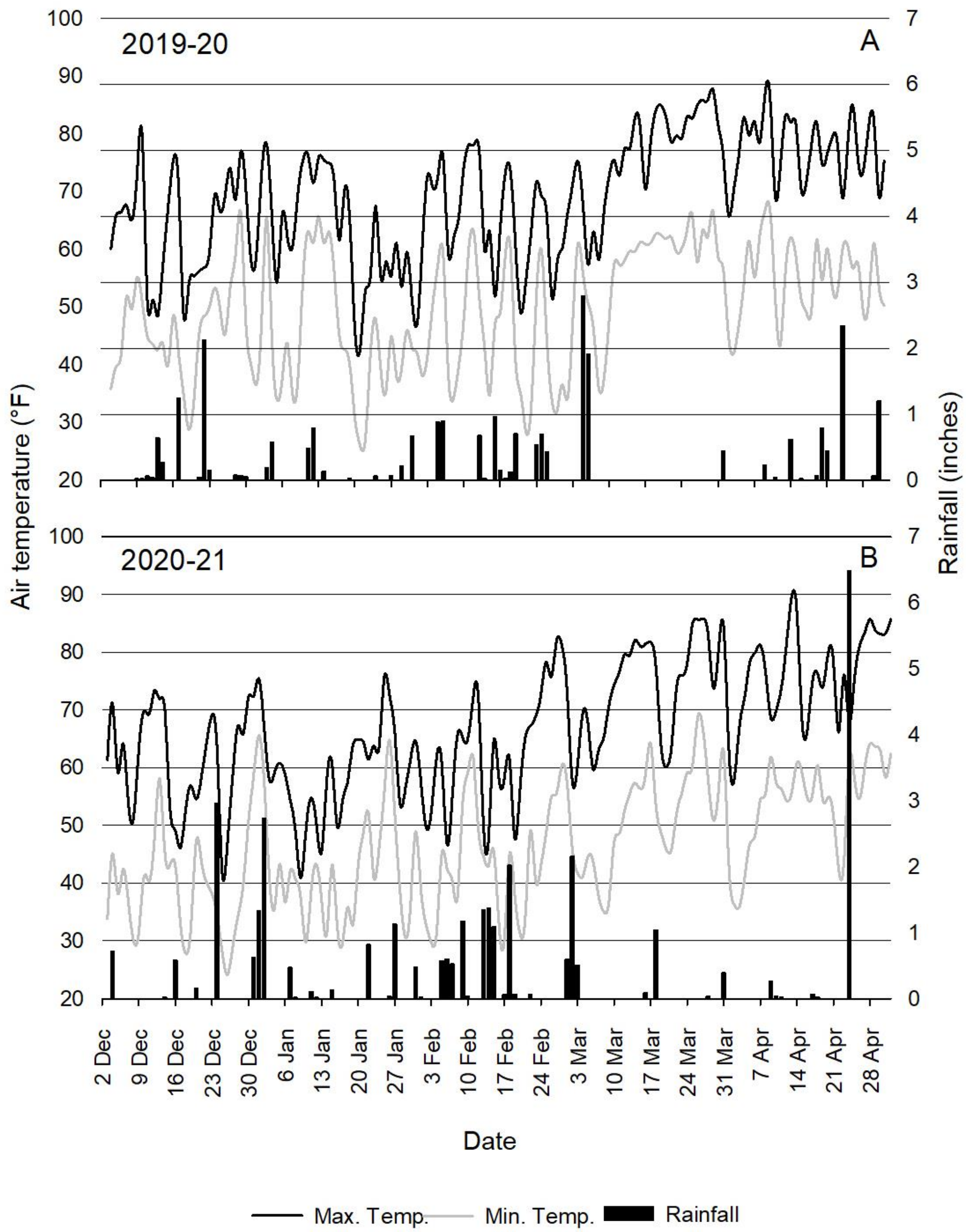

Fig. 5.5. Average daily maximum and minimum air temperatures and accumulated rainfall for the 2019-20 (A) and 2020-21 (B) for study location for onion (*Allium cepa*) grown in Tifton, GA, USA; (^{o}F - 32) ÷ 1.8 = ^{o}C, 1 inch = 2.54 cm.

Daily maximum and minimum air temperatures were greater in Tifton, GA than in Watkinsville, GA. Daily maximum temperatures averaged 69.3 ^{o}F in 2019-20 and 67.0 ^{o}F in 2020-21 in Tifton and 62.7 and 61.7 ^{o}F in 2019-20 and 2020-21, respectively, in Watkinsville. The 2019-20 growing season had 6 and 17 d of daily minimum air temperatures below freezing in Tifton and Watkinsville, respectively. In contrast, the 2020-21 growing season had more freeze events, with 14 and 31 d with daily minimum air temperatures below freezing in Tifton and Watkinsville, respectively.

Total marketable onion yields were affected by interactions between the fertilizer source and location (Table 5.2). An average total yield of 14,559 lb/acre was obtained with the use of the MIX fertilizer in Watkinsville. This was greater than the 10,470 lb/acre yield obtained with the use of the PPL fertilizer in the same location. In Tifton, total yields were 10,216 and 8336 lb/acre for the MIX and PPL fertilizers, respectively.

Table 5.2. Effects of pelleted poultry litter [PPL (5N-1.8P-2.5K)] and mixed-source organic [MIX (10N-0.88P-6.6K)] fertilizers and location on total yield of organically grown onion (*Allium cepa*) in Watkinsville and Tifton, GA, USA.

Fertilizer	Watkinsville		Tifton	
	Yield (lb/acre)[i]			
MIX	14,558	a[ii]	10,216	bc
PPL	10,470	b	8,336	c

[i]1 lb/acre =1.1209 kg·ha^{-1}.

[ii]Values followed by the same letter indicate are not significantly different at $P \leq 0.05$ according to the Tukey's honest significant difference test.

Total marketable yield was also impacted by an interaction among location, application rate, and year (Fig. 5.3). Because there was not a significant four-way interaction, fertilizer sources were pooled by application rate. The total marketable yield of organic onions in both years and locations increased linearly with increasing N application rate. In Watkinsville, total yields of onions at different N rates ranged between 1320-4565 lb/acre in 2019-20, and between 9951-28,749 lb/acre in 2020-21. In Tifton, ranges of total yields were 3776-9264 lb/acre and 7094-14,066 lb/acre in 2019-20 and 2020-21 seasons, respectively. Although yields in 2019-20 in both locations and yields in 2020-21 in Tifton were considerably lower than commercial yields for the region, in 2020-21 onion total yields in Watkinsville with the addition of 200 to 300lb/acre N from organic fertilizers were comparable to the yield of onions receiving 134 lb/acre N of synthetic fertilizer (Díaz-Pérez et al., 2021). In the present study, we utilized a population of 58,080 plants per acre, as is typical for organic onions. However, many conventional farms in the region have adopted a population of 87,120 plants per acre. Further, in 2019-20, excessive rainfall in Watkinsville negatively impacted developing plants, contributing to a reduction in onion populations. Although air temperatures were greater in 2019-20 compared to 2020-21, a rain event of 3.69 inches on 13 Dec 2019 coupled with 4 d with minimum air temperatures below freezing shortly after planting resulted in reduced transplant survival (data not shown) in some plots for the Watkinsville location. No differences in plant survival were noted among fertilizer treatments. Overall yield responses to fertilizer rates are similar to those reported by Boyhan et al. (2010), who reported a linear response of organic onion yields to increased preplant applications of PL. Díaz-Pérez et al. (2018a) reported a quadratic response of onion marketable yield to increasing rates of a PPL-based fertilizer, with application rates ranging from 0 to 240 $kg \cdot ha^{-1}$.

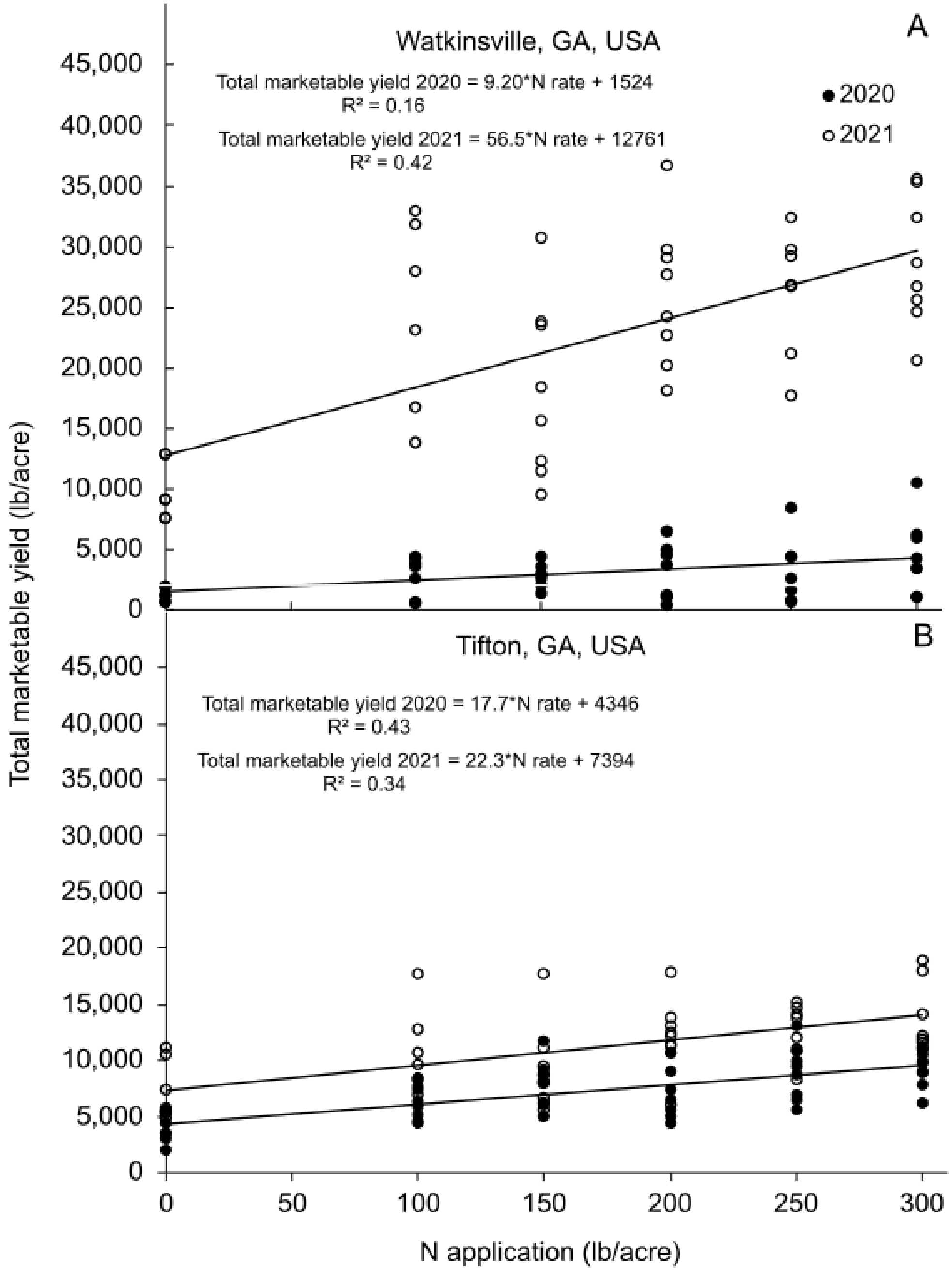

Fig. 5.3. Effect of nitrogen (N) application rates on total marketable yield of organically grown onion (*Allium cepa*) in Watkinsville (A) and Tifton (B) GA, USA during the 2019-20 and 2020-21 growing seasons; 1 lb/acre =1.1209 kg·ha^{-1}.

Bulb disease was also evaluated at harvest; however, there were no bacterial diseases detected in any of the bulb subsamples in either location or study year (data not shown). Further, visual assessment of the study during growth indicated that very little to no disease was present at either location.

Soil inorganic N at harvest was impacted by the interaction between fertilizer source and year (Table 5.3). In 2020, there were no differences in soil inorganic N at harvest between plots receiving the MIX (9 lb/acre N) or PPL (9.8 lb/acre N) in either location. In 2021, soil inorganic N was greater in plots receiving the MIX fertilizer (14.8 lb/acre N) compared to the PPL fertilizer (11.2 lb/acre N). Nitrogen availability in soil varies with chemical composition of organic fertilizers (Cabrera et al., 2005; Cassity-Duffey et al., 2020a, 2020b; Sänger et al., 2010). Comparing different N sources, Agehara & Warncke (2005) reported that increasing soil moisture levels also enhanced N release from alfalfa pellets and PL but did not significantly affect N released from urea and blood meal. Moreover, the pattern of release also varied with composition of N sources; with mineralization of alfalfa pellets and PL increasing with high soil moisture levels during latter phases of incubation. In contrast, mineralization of blood meal was enhanced during the initial phase of incubation. Authors suggested that microbial communities responsible for N mineralization may be distinguished over time and are differentially impacted by soil moisture content.

Table 5.3. Effect of pelleted poultry litter [PPL (5N-1.8P-2.5K)] and mixed-source organic [MIX (10N-0.88P-6.6K)] fertilizers and study year on soil inorganic nitrogen (N) at harvest for organically grown onion (*Allium cepa*) in Georgia, USA.

Fertilizer	2020	2021
	Soil inorganic N	

	(lb/acre)[i]			
MIX	9.0	b[ii]	14.8	a
PPL	9.8	b	11.2	b

[i]1 lb/acre =1.1209 kg·ha^{-1}.

[ii]Values followed by the same letter indicate are not significantly different at $P \leq 0.05$ according to the Tukey's honest significant difference test.

Rainfall levels in 2019-20 may have contributed to increased N leaching during the season, leading to the lack of significant differences in soil inorganic N between the MIX and PPL plots. However, with reduced rainfall in Watkinsville 2020-21, there was more soil inorganic N in MIX treated soils at harvest. The PPL fertilizer had more than twice the amount of inorganic N at application, suggesting that there was more readily leachable N at planting in the PPL compared to the MIX fertilizer. The N availability in soils is significantly influenced by precipitation and the resulting soil water dynamics. These effects are mediated through physical transport processes and microbial N transformations in the soil (Aranibar et al., 2004; Gu & Riley, 2010). Using a modeling approach, Gu & Riley (2010) reported that precipitation patterns can have significant impacts on soil N cycling and losses, which were also influenced by soil texture and other soil characteristics. Increased N loss in 2019-20 could have also contributed to lower yields in that growing season. The process of pelletizing PL may also influence mineralization, as it can create favorable conditions for microbial activity and the transformation of N to its inorganic form (Hadas et al., 1983). During a season without excessive rainfall, the MIX fertilizer may be subjected to less potential soil N leaching, particularly on the clay loam soils in the Watkinsville location.

Aboveground onion N accumulation at harvest was affected by an interaction among location, study year, and fertilizer rate (Table 5.4). The largest plant N accumulation was in Watkinsville in 2020-21, ranging from 26 to 50.8 lb/acre N in the 0 and 300 lb/acre N treatments, respectively. On-farm surveys in the Vidalia region have indicated an average above-ground N accumulation in plants at harvest of approximately 66 lb/acre of N, though values can be greater than 100 lb/acre N in heavily fertilized fields (Coolong T, unpublished data). Nitrogen accumulation was greater in onion plants receiving organic fertilizer rates between 200 to 300 lb/acre N compared to plants that did not receive any fertilizer. Previously N accumulation in leaves and bulbs has been reported to be correlated with increasing N fertilization (Díaz-Pérez et al., 2003). In 2019-20 in Watkinsville, plant N accumulation increased with N application rate; however, it was not different in plants receiving between 0 to 250 lb/acre N fertilizer. As N accumulation is a function of total biomass and N concentration, this low N uptake was likely the result of low yields (total biomass) in Watkinsville in the 2019-20 growing season. In Tifton, plant N accumulation at harvest was unaffected by fertilizer application rate in 2019-20, while N uptake from onion plants increased with increasing N application rate in 2020-21. Aboveground N accumulation was lower in 2019-20 in both Watkinsville and Tifton locations, compared to 2020-21 for every treatment except for the 0 lb/acre N treatment in Tifton (Table 4). Díaz-Pérez et al. (2018b) reported that despite high fertilization rates, nutrient deficiencies were observed late in the season in organically grown onions in Tifton, GA, USA. These findings suggest that exclusive preplant application of organic fertilizers may result in leaching nutrients mineralized during the season.

Table 5.4. Effect of the interaction among location, year, and application rate on aboveground plant nitrogen (N) accumulation at harvest for organically grown onion (*Allium cepa*) in Watkinsville and Tifton, GA, USA.

	2020	**2021**
Treatments	Plant N accumulation at harvest (lb/acre)[i]	

Watkinsville				
0	5.8	B[ii] b[iii]	26.0	B a
100	6.4	AB b	37.4	AB a
150	6.8	AB b	34.6	AB a
200	8.0	AB b	47.2	A a
250	7.9	AB b	50.8	A a
300	10.8	A b	50.8	A a
Tifton				
0	6.7	A a	11.7	B a
100	7.6	A b	16.2	AB a
150	9.2	A b	16.4	AB a
200	10.3	A b	16.7	AB a
250	11.1	A b	18.8	AB a
300	10.6	A b	25.3	A a

[i]1 lb/acre =1.1209 $kg \cdot ha^{-1}$.
[ii]Values within the same column followed by the same upper-case letter(s) within the same location and year are not significantly different at $P \leq 0.05$ according to the Tukey's honest significant difference test.
[iii]Values within the same row and location followed by the same lower-case letter are not significantly different at $P \leq 0.05$ according to the Tukey's honest significant difference test.

Aboveground N accumulation at harvest was also affected by an interaction between fertilizer source and location (Table 5.5). The accumulation of 27.0 lb/acre N was observed in plants receiving the MIX fertilizer in Watkinsville, followed by 20.4 lb/acre N accumulation in plants receiving the PPL fertilizer in the same location. In Tifton, there was no significant difference in plant N accumulation at harvest among fertilizer sources. While N accumulation is a function of plant biomass (yield) and N concentration it is possible that differences in plant N accumulation may be also linked to in N availability, which can differ among fertilizers and is impacted by soil characteristics (Agehara & Warncke, 2005; Cassity-Duffey et al., 2020a).

Table 5.5. Effect of the interaction between pelleted poultry litter [PPL (5N-1.8P-2.5K)] and mixed-source organic [MIX (10N-0.88P-6.6K)] fertilizers and growing location on aboveground total nitrogen (N) accumulation at harvest for organically grown onion (*Allium cepa*) in Watkinsville and Tifton, GA, USA.

Fertilizer	Aboveground plant N accumulation (lb/acre) [i]			
	Watkinsville		Tifton	
MIX	27.0	a[ii]	14.4	c
PPL	20.4	b	12.3	c

[i]1 lb/acre =1.1209 kg·ha^{-1}.

[ii]Values followed by the same letter indicate are not significantly different at $P \leq 0.05$ according to Tukey's honest significant difference test.

Plant N uptake was measured throughout crop development in 2020-21 season and was affected by an interaction among location, fertilizer source, and N rate. Despite the interaction, overall trends were similar among N rates; therefore, data corresponding to the mid-point application rate of 200 lb/acre N is presented (Fig. 5.4). Plant N uptake increased during the season and was greater for onions grown in Watkinsville compared to Tifton. In Tifton, there were no differences for N uptake between PPL and MIX fertilizers. However, in Watkinsville, N uptake in plants was greater for plants grown with the MIX fertilizer on 3 Feb 2021, when plants were actively growing vegetatively. On 1 Apr 2021, during the bulb swelling stage of onions, plants accumulated greater amounts of N with the MIX fertilizer compared to PPL. In onion, low N accumulation in the aboveground biomass is expected early in the season, but as bulb development is initiated, the N requirements increase, with N uptake only slowing during bulb maturation (Geisseler et al., 2022). It is important that N mineralization rates align with crop requirements, ensuring an efficient utilization of organic fertilizers.

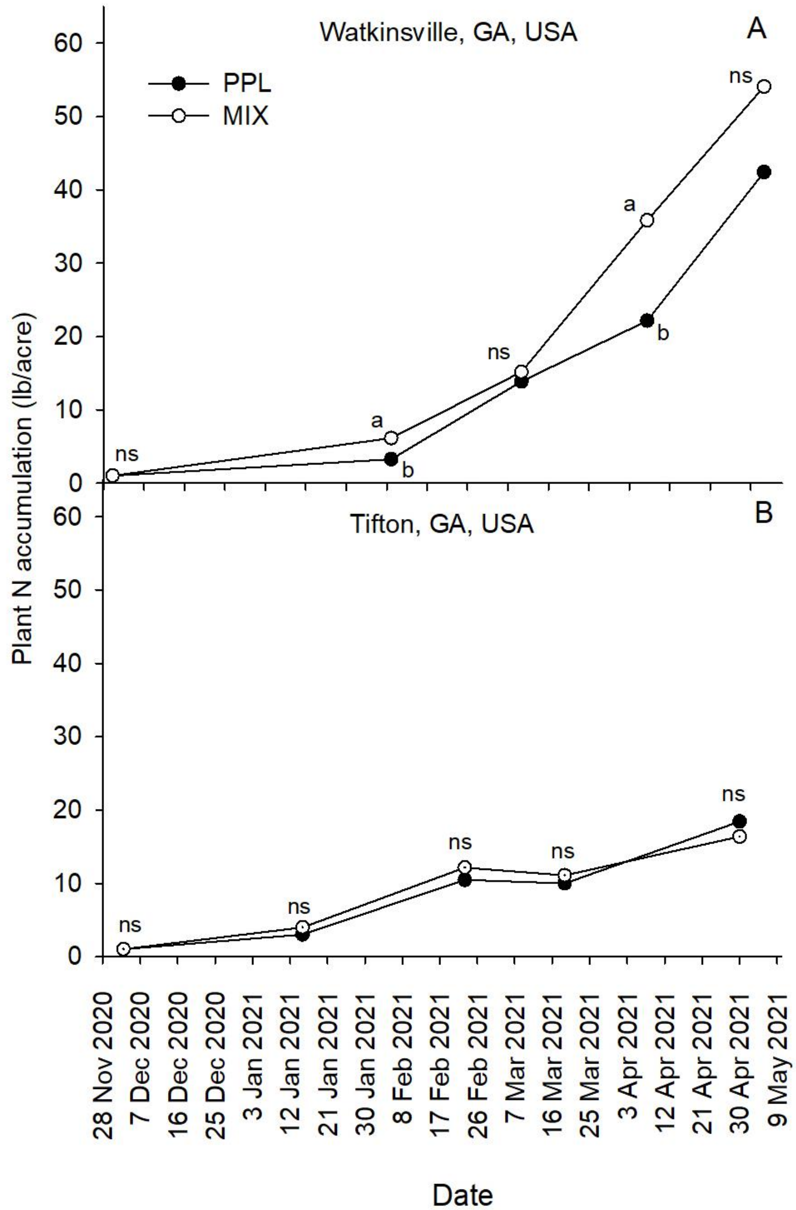

Fig. 5.4. Effects of the application of 200 lb/acre nitrogen (N) of pelleted poultry litter [PPL (5N-1.8P-2.5K)] and mixed-source organic [MIX (10N-0.88P-6.6K)] fertilizers on aboveground plant N uptake during the 2020-21 season for organic onions grown in Watkinsville (A) and Tifton (B). Sample dates associated with the same letter and location are not significantly different according to Tukey's honest significant difference test ($P \leq 0.05$); ns = non-significant, 1 lb/acre =1.1209 $kg{\cdot}ha^{-1}$.

There was a significant year by location by fertilizer source by rate interaction for onion NUPE (Table 5.6). Because NUPE is a function of dry matter accumulation (yield) values were low in 2020 in both study locations. In Watkinsville in 2019-20 NUPE for the MIX fertilizer averaged 4.40% to 8.11% in the 300 and 100 lb/acre N application rates, respectively, while the NUPE for the PPL product averaged 2.78%. In Tifton, NUPE values were similarly low. In 2021-22, NUPE were 50.44% and 20.99% for the MIX fertilizer applied at 100 lb/acre N in Watkinsville and Tifton locations, respectively. There were no differences in NUPE for the PPL applied in Watkinsville in either year; however, there were differences in NUPE for PPL in Tifton in both study years. In 2020-21 NUPE was significantly greater in both locations than in 2019-20 (data not shown). The NUPE values obtained in this study were considerably lower than those obtained by Drost et al. (2002) using a conventional urea-based fertilizer. Mineralization rates of both PPL and MIX products utilized in this study were previously determined in a soil incubation study using a Cecil sandy clay loam soil, which is the same soil as the Watkinsville location in the present study (Cassity-Duffey et al., 2020b). In that study only 20% of organic N in the PPL mineralized after 99 d, while 60% of the organic N from the MIX product was available after 99 d. Further, the greater amount of inorganic N in the PPL product (23.8% of total N) may have leached early in the season, particularly with heavy rainfall. The NUPE (50.44%) obtained in Watkinsville in 2020-21 using the MIX product at 100 lb/acre N suggests that a large portion of the N that was likely mineralized and available was taken up by the plants. As would be expected, NUPE decreased with increasing N application rates. In the present study, the addition of MIX fertilizer to onion plants in the Watkinsville location may have favored plant N uptake by providing either a higher rate of N release or matching the release time with plant N-requirements.

Table 5.6. Effects of pelleted poultry litter [PPL (5N-1.8P-2.5K)] and mixed-source organic [MIX (10N-0.88P-6.6K)] fertilizers applied at different rates for nitrogen uptake efficiency (NUPE) of organically grown onion (*Allium cepa*) in Watkinsville and Tifton, GA, USA in 2020 and 2021.

Treatments	**2020** NUPE[ii] (%)		**2021**	
Watkinsville				
PPL				
100	5.32	a[i]	26.35	a
150	3.14	a	16.54	a
200	1.76	a	21.22	a
250	1.50	a	14.28	a
300	2.20	a	17.76	a
MIX				
100	8.11	a	50.44	a
150	5.44	ab	30.93	b
200	5.72	ab	27.04	bc
250	4.38	b	22.00	bc
300	4.40	b	16.78	c
Tifton				
PPL				
100	7.55	a	13.37	a
150	7.20	a	11.55	ab
200	3.45	b	9.22	ab
250	5.08	ab	7.66	ab
300	3.53	b	7.08	b
MIX				
100	10.01	a	20.99	a
150	6.67	a	12.06	ab
200	8.05	a	8.19	b
250	4.72	a	10.46	ab
300	4.35	a	8.20	b

[i]NUPE = Total N uptake in the plant / total N applied.
[ii]Values within the same column followed by the same upper-case letter(s) within the same year, location and fertilizer type are not significantly different at $P \leq 0.05$ according to the Tukey's honest significant difference test.

Conclusions

The total yield of organic onions increased with increasing organic fertilizer rates as would be expected, though NUPE significantly decreased with increasing application rate. Onions grown in the Watkinsville location had a greater N aboveground accumulation compared to those grown in Tifton. Further, the relatively high level of inorganic N in the PPL fertilizer would have been available early in the season when onions may have had low N requirements (Coolong et al., 2004). Higher N accumulation at harvest and plant N uptake over the season was obtained with the application of MIX fertilizer compared to the application of PPL fertilizer. In 2020-21 the total yield of Vidalia onions in Watkinsville was significantly higher with the use of MIX fertilizer and was comparable to yields of onions receiving conventional synthetic fertilizers (Díaz-Pérez et al., 2021). Overall, there were no effects of fertilizer treatments in onions grown in Tifton. Our findings suggest that the MIX fertilizer may be more effective than the PPL fertilizer for organic onion production in some seasons. Further, NUPE of the PPL product in all locations and years suggest that less N from the PPL product was taken up by onions during the cropping season. While yields increased linearly with application rate, a low NUPE, particularly for the PPL fertilizer, suggests that high N application rates of these organic are inefficient.

Literature Cited

Agehara, S., & Warncke, D. D. (2005). Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. *Soil Science Society of America Journal*, *69*(6), 1844-1855. https://doi.org/10.2136/sssaj2004.0361

Aranibar, J. N., Otter, L., Macko, S. A., Feral, C. J., Epstein, H. E., Dowty, P. R., ... & Swap, R. J. (2004). Nitrogen cycling in the soil–plant system along a precipitation gradient in the Kalahari sands. *Global Change Biology*, *10*(3), 359-373. https://doi.org/10.1111/j.1365-2486.2003.00698.x

Berry, P. M., Sylvester-Bradley, R., Philipps, L., Hatch, D. J., Cuttle, S. P., Rayns, F. W., & Gosling, P. (2002). Is the productivity of organic farms restricted by the supply of available nitrogen?. *Soil Use and Management*, *18*, 248-255. https://doi.org/10.1111/j.1475-2743.2002.tb00266.x

Boyhan, G. E., Hicks, R., Torrance, R.., Hopkins, C., Riner C., Hill, R., & Paulk, T. (2007). Organic Vidalia onion production: The basics of what works, what you can do and what you can't. https://hdl.handle.net/10724/33582. (accessed 25 Feb 2023).

Boyhan, G. E., Hicks, R., Torrance, R., Riner, C. M., & Hill, C. R. (2010). Evaluation of poultry litter and organic fertilizer rate and source for production of organic short-day onions. *HortTechnology*. *20*(2), 304–307. https://doi.org/10.21273/HORTTECH.20.2.304

Cabrera, M. L., Kissel, D. E., & Vigil, M. F. (2005). Nitrogen mineralization from organic residues: Research opportunities. *Journal of environmental quality*, *34*(1), 75-79. https://doi.org/10.2134/jeq2005.0075

Calderón, F. J., McCarty, G. W., & Reeves, J. B. (2005). Analysis of manure and soil nitrogen mineralization during incubation. *Biology and Fertility of soils*, *41*, 328-336. https://doi.org/10.1007/s00374-005-0843-x

Cassity-Duffey, K., Cabrera, M., Gaskin, J., Franklin, D., Kissel, D., & Saha, U. (2020a). Nitrogen mineralization from organic materials and fertilizers: Predicting N release. *Soil Science Society of America Journal*, *84*(2), 522-533. https://doi.org/10.1002/saj2.20037

Cassity-Duffey, K., Cabrera, M., Franklin, D., Gaskin, J., & Kissel, D. (2020b). Effect of soil texture on nitrogen mineralization from organic fertilizers in four common southeastern soils. *Soil Science Society of America Journal*, *84*(2), 534-542. https://doi.org/10.1002/saj2.20039

Cassity-Duffey, K. B., Moore, A., Satterwhite, M., & Leytem, A. (2018). Nitrogen mineralization as affected by temperature in calcareous soils receiving repeated applications of dairy manure. *Soil Science Society of America Journal*, *82*(1), 235-242. https://doi.org/10.2136/sssaj2017.02.0044

Chastain, J. P., Camberato, J. J., & Skewes, P. (2001). Poultry manure production and nutrient content. In: Confined animal manure managers certification program manual: Poultry version. https://www.clemson.edu/extension/camm/manuals/poultry/pch3b_00.pdf (accessed 25 Feb 2023)

Coolong, T., & Boyhan, G. (2017). Onion production guide. *University of Georgia Cooperative Extension Bulletin* 1198.

Coolong, T. W., Kopsell, D. A., Kopsell, D. E., & Randle, W. M. (2005). Nitrogen and sulfur influence nutrient usage and accumulation in onion. *Journal of plant Nutrition*, *27*(9), 1667-1686. https://doi.org/10.1081/PLN-200026010.

Coolong, T. W., & Randle, W. M. (2003). Ammonium nitrate fertility levels influence flavour development in hydroponically grown 'Granex 33'onion. *Journal of the Science of Food and Agriculture*, *83*(5), 477-482. https://doi.org/10.1002/jsfa.1398

Díaz-Pérez, J. C., Bautista, J., Gunawan, G., Bateman, A., & Riner, C. M. (2018a). Sweet onion (Allium cepa L.) as influenced by organic fertilization rate: 1. Plant growth, and leaf and bulb mineral composition. *HortScience*, *53*(4), 451-458. https://doi.org/10.21273/HORTSCI12791-17

Díaz-Pérez, J. C., Bautista, J., Gunawan, G., Bateman, & A., Riner, C. M. (2018b). Sweet onion (*Allium cepa L*.) as influenced by organic fertilization rate: 2. Bulb yield and quality before and after storage. *HortScience*. *53*(4), 459-464. https://doi.org/10.21273/HORTSCI12360-17

Díaz-Pérez, J. C., da Silva, A. L. B. R., & Valdez-Aguilar, L. A. (2021). Seasonal plant growth, leaf and bulb mineral nutrients, and bulb yield and quality under chemical, mixed, and organic fertilization in sweet onion (*Allium cepa L*.). *Journal of Plant Nutrition*, *45*(2), 153-167. https://doi.org/10.1080/01904167.2021.1952227

Díaz-Pérez, J. C., Purvis, A. C., & Paulk, J. T. (2003). Bolting, yield, and bulb decay of sweet onion as affected by nitrogen fertilization. *Journal of the American Society for Horticultural Science*, *128*(1), 144-149. https://doi.org/10.21273/JASHS.128.1.0144

Drost, D., Koenig, R., & Tindall, T. (2002). Nitrogen use efficiency and onion yield increased with a polymer-coated nitrogen source. *HortScience. 37*(2), 338-342. https://doi.org/10.21273/HORTSCI.37.2.338.

Dunkley, C. S., Cunningham, D. L., & Harris, G. H. (2011). The value of poultry litter in South Georgia. *University of Georgia Cooperative Extension Bulletin* 1386.

Evers, G. W. (1998). Comparison of broiler poultry litter and commercial fertilizer for coastal bermudagrass production in the southeastern US. *Journal of Sustainable Agriculture*, *12*(4), 55-77. https://doi.org/10.1300/J064v12n04_06

Gale, E. S., Sullivan, D. M., Cogger, C. G., Bary, A. I., Hemphill, D. D., & Myhre, E. A. (2006). Estimating plant-available nitrogen release from manures, composts, and specialty products. *Journal of Environmental Quality*, *35*(6), 2321-2332. https://doi.org/10.2134/jeq2006.0062

Geisseler, D., Ortiz, R. S., & Diaz, J. (2022). Nitrogen nutrition and fertilization of onions (*Allium cepa* L.)–A literature review. *Scientia Horticulturae*, *291*, 110591. https://doi.org/10.1016/j.scienta.2021.110591

Gitaitis, R. D., Gent, D.H., & Schwartz, H. S. (2008). Leaf streak and bulb rot. In: Schwartz, H. F., Mohan, S. K. (eds). *Compendium of onion and garlic disease and pests*. APS Press, St. Paul, MN.

Gu, C., & Riley, W. J. (2010). Combined effects of short term rainfall patterns and soil texture on soil nitrogen cycling—A modeling analysis. *Journal of contaminant hydrology*, *112*(1-4), 141-154. https://doi.org/10.1016/j.jconhyd.2009.12.003

Hadas, A., Bar-Yosef, B., Davidov, S., & Sofer, M. (1983). Effect of pelleting, temperature, and soil type on mineral nitrogen release from poultry and dairy manures. *Soil Science Society of America Journal*, *47*(6), 1129-1133. https://doi.org/10.2136/sssaj1983.03615995004700060014x

Hartz, T. K., & Johnstone, P. R. (2006). Nitrogen availability from high-nitrogen-containing organic fertilizers. *HortTechnology*. *16*(1), 39-42. https://doi.org/10.21273/HORTTECH.16.1.0039

Islam, M., Doyle, M. P., Phatak, S. C., Millner, P., & Jiang, X. (2005). Survival of Escherichia coli O157: H7 in soil and on carrots and onions grown in fields treated with contaminated manure composts or irrigation water. *Food microbiology*, *22*(1), 63-70. https://doi.org/10.1016/j.fm.2004.04.007

Li-Xian, Y., Guo-Liang, L., Shi-Hua, T., Gavin, S., & Zhao-Huan, H. (2007). Salinity of animal manure and potential risk of secondary soil salinization through successive manure application. *Science of the total environment*, *383*(1-3), 106-114. https://doi.org/10.1016/j.scitotenv.2007.05.027

Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature Plants. 2*(2), 1-8. https://doi.org/10.1038/nplants.2015.221

Sänger, A., Geisseler, D., & Ludwig, B. (2010). Effects of rainfall pattern on carbon and nitrogen dynamics in soil amended with biogas slurry and composted cattle manure. *Journal of Plant Nutrition and Soil Science*, *173*(5), 692-698. https://doi.org/10.1002/jpln.200900254

Sharpley, A. N. (1997). Rainfall frequency and nitrogen and phosphorus runoff from soil amended with poultry litter. *Journal of Environmental Quality, 26*(4):1127-1132. https://doi.org/10.2134/jeq1997.00472425002600040026x

Tyson, C., Jackson, D., da Silva, A. L. B. R., Edenfield, J., Shirly, A., Bowen, D., Thigpen, D., Clark, D., Powell, S., Tanner, S., & Greene, S. (2023). UGA variety trial report for the 2020-21 Vidalia onion crop season. 2022 Vidalia Onion Extension and Research Report. *University of Georgia Cooperative Extension Bulletin* AP114-1. https://site.extension.uga.edu/vidaliaonion/2023/04/2022-vidalia-onion-research-extension-report/ (accessed 17 Apr 2023).

University of Georgia. (2020). Fertilizer recommendations by crops. http://aesl.ces.uga.edu/cropcodelist.pdf. (accessed 7 Apr 2023).

University of Georgia. (2022a). 2021 Georgia farm gate value report. *University of Georgia Cooperative Extension Bulletin* AR 22-01. https://caed.uga.edu/publications/farm-gate-value.html (accessed 25 Feb 2023).

University of Georgia. (2022b). Watkinsville and Tifton Georgia climate data. http://www.georgiaweather.net/. (accessed 20 Feb 2023).

US Department of Agriculture. (2014). United states standards for grades of Bermuda-Granex-Grano type onions. *US Department of Agriculture*, Washington, DC.

US Department of Agriculture. (2019). Census of Agriculture – 2019 Organic Survey. *US Department of Agriculture*, Washington, DC. https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Organics/ (accessed 25 Feb 2023).

US Department of Agriculture. (2022). Soil survey. Web soil survey – Soil survey of Oconee and Tift Counties, Georgia. https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx. (accessed 28 Mar 2023).

US Department of Agriculture, National Agricultural Statistics Service. (2022). Poultry–Production and value 2021 summary. https://downloads.usda.library.cornell.edu/usda-esmis/files/m039k491c/dr2703010/v405tf48t/plva0422.pdf (accessed 17 April 2023).

US Food and Drug Administration. (2020). 2020 Recalls of Food Products Associated with Onions from Thomson International, Inc. Due to the Potential Risk of Salmonella. https://www.fda.gov/safety/major-product-recalls/2020-recalls-food-products-associated-onions-thomson-international-inc-due-potential-risk-salmonella (accessed 25 Feb 2023).

CHAPTER 6

INFLUENCE OF SOIL AND TEMPERATURE ON PLANT AVAILABLE NITROGEN FROM ORGANIC FERTILIZERS[4]

[4] de Jesus, H. I., Cassity-Duffey, K., Dutta, B, da Silva, A.L.B.R., & Coolong, T. (2023). To be submitted to *Sustainability*.

Abstract

Organic vegetable producers in Georgia, USA, utilize various amendments to supply nitrogen (N) for crop production. However, differences in soil type and environmental conditions can result in variability in N mineralization rates among commonly utilized organic fertilizers in the region. In this study, the effects of temperature on N mineralization from three commonly used organic fertilizers, feather meal (FM), pelleted poultry litter (PPL) and a mixed organic fertilizer (MIX) in two soil types (Cecil sandy clay loam and Tifton loamy sand) that are found in Georgia, USA, were evaluated during a 120 d incubation study. Net N mineralization Net N_{min} varied with soil type, fertilizer, and temperature. After 120 d, Net N_{min} from the FM fertilizer ranged between 42% and 72% of total N applied, followed by the MIX fertilizer (between 26% and 59%), while the PPL fertilizer had a Net N_{min} between 0% and 22% when averaged over soil type and temperature. Temperature and soil had a relatively minor impact on the potentially mineralizable N of the MIX and PPL fertilizers after 120 d; however, the higher incubation temperatures (20°C and 30°C) negatively impacted Net N_{min} of FM fertilizer in the Tifton soil after 56 d of incubation.

Introduction

Continued growth in organic vegetable production in the USA has led to increased demand for alternatives to chemical fertilizers for nutritional needs, particularly when it comes to crop nitrogen (N) requirements. A range of organic materials are commonly used in agricultural systems, including cover crop residues, composts, manures, slaughter byproducts, and commercial organic fertilizers derived from various animal or plant sources (Bergstrand, 2022; Gale et al., 2006). However, unlike readily soluble synthetic fertilizers, the availability of nutrients from organic amendments and fertilizers can be highly variable (Wortman et al., 2017). Because organic fertilizers may include some levels of readily available organic N, ammonium (NH_4), and nitrate

(NO_3), N availability may differ widely among sources (Cassity-Duffey et al. 2020a). Failure to coordinate the timing of N release from organic fertilizers with the nutritional demands of crops may result in N loss and reduced productivity. Thus, it is important to be able to accurately predict N mineralization rates from organic fertilizers and determine the mechanisms that impact N mineralization from organic sources (Cabrera et al., 2005; Cassity-Duffey et al., 2020b; Reganold & Wachter, 2016).

Nitrogen present in organic forms must go through microbial-mediated mineralization to be converted into plant-available NH_4 and NO_3 (Plante & Parton, 2007). Organic fertilizers may differ widely in physicochemical characteristics, and N mineralization can vary depending on the properties of materials added, such as total N concentration, initial inorganic N concentration, and carbon to nitrogen (C:N) ratio (Calderón et al., 2004; Geisseler et al., 2010). In vitro incubation and field-based studies have shown that net N mineralization (Net N_{min}) among different organic amendments can vary between 20% to 93% of the total N applied (Agehara & Warnacke, 2005; Cassity-Duffey et al., 2020a; Hartz and Johnson, 2006). However, the physiochemical characteristics of the materials themselves do not explain all the variability observed in N mineralization among fertilizers, and further information is needed to correctly predict N release after application (Lazicki et al., 2019; Geisseler et al., 2021).

In addition to the physiochemical characteristics of organic fertilizers, the release of N from these products is a function of environmental conditions and soil properties that affect N decomposition in soils (Lazicki et al., 2020). Microorganisms in the soil promote N mineralization through enzymatic reactions, primarily controlled by temperature and humidity (Dessureault-Rompré et al., 2010; Guntiñas et al., 2012; Sierra, 1997). In general, the mineralization rate in the soil increases with soil temperature up to a maximum and then declines (Agehara & Warncke, 2005; Bowles et al., 2014; Miller & Geisseler, 2018). Therefore, weather fluctuations during the season or across regions may impact the rate of N mineralization in the soil (Sierra, 2002). Several studies have evaluated the effects of temperature on N mineralization from soil organic matter (Gonçalves & Carlyle, 1994; Guntiñas et al., 2012; Knoepp & Swank, 2002; Sierra, 1997). However, research on N mineralization from organic fertilizers suggests that N transformations at different temperatures are likely to be dependent on a complex interaction between soil microorganisms and the mineralizable substrates in the amendment (Agehara and Warncke, 2005; Cassity-Duffey et al., 2018; Sims, 1986). Factors such as the C:N ratio of the organic materials have been reported to be closely linked to N mineralization of a range of organic amendments (Gale et al., 2006). Temperature has also been shown to influence N availability, depending on material composition (Lazicki et al., 2019). Studies suggest that N mineralization of high-N-containing materials is primarily influenced by temperature during the initial days after incorporation, whereas low-N-containing materials are more susceptible to temperature variations over an extended period (Agehara & Warncke, 2005; Hartz and Johnstone, 2006; Hart et al., 2010; Lazicki et al., 2019).

In addition to environmental conditions, soil physical and/or chemical properties can alter the N mineralization of organic materials due to changes in the soil microbiota and the enzymatic reactions that drive the N release (Geisseler et al., 2010; Lazicki et al., 2019; Stanford and Smith, 1972). Further, soil type can significantly affect N mineralization (Gordillo and Cabrera, 1997; Hassink et al., 1993; Van Veen et al., 1985). In general, fine-textured soils with high clay contents have been reported to have lower N mineralization rates than coarse-textured, sandy soils, which is likely due to factors such as physical isolation of organic matter by clay particles or entrapment in small pores, where a substrate may be inaccessible to microorganisms (Hassink et al., 1993;

Soinne et al., 2020). Cassity-Duffey et al. (2020b) determined that, after 100 d of incubation, soil texture had an impact on the rate of N release but had minimal effects on total mineralizable N for two organic fertilizers, a feather meal and a pelleted fertilizer blend (Cassity-Duffey et al., 2020b). Similarly, Lazicki et al. (2019) found that soil texture and management history did not consistently affect Net N_{min} from 22 different organic materials but may have influenced the rate of N release.

Understanding the factors affecting the N release from organic fertilizers is important to determine the rate and timing of application. Models have been proposed to simulate the N release from organic soil amendments in the field (Agehara & Warncke, 2005; Cassity-Duffey et al., 2018; de Neve & Hofman, 1998; Honeycutt, 1999; Kaupa & Rao, 2014; Lei & McDonald, 2019). Although different kinetics may be utilized to predict N availability, first-order kinetic models are often used to predict the N mineralization potential (N_0) from different amendments, where the rate at which N mineralizes is assumed to be proportional to the amount of soil N available for mineralization (Cabrera et al., 2008; Stanford & Smith, 1972). An accurate estimate of N mineralization from organic fertilizers that models the impact of temperature on the mineralization rate would be a useful tool for organic vegetable growers. However, data are lacking on the impacts of temperature on N mineralization from these products. Thus, the objectives of this study are to determine the effects of four temperatures and two soil textures on three commercially available organic fertilizers commonly used for vegetable production in Georgia, USA through a 120 d laboratory incubation.

Materials & Methods

Soil and organic fertilizers

The soils used in this study represented two common agricultural soil series in Georgia, USA. Soils were collected from US Department of Agriculture (USDA) certified organic land at the University of Georgia (UGA) Durham Horticulture Farm in Watkinsville, GA, USA (lat. 33º 5'N, long. 83º 3'W) and at the UGA Horticulture Farm in Tifton, GA, USA (lat. 31º 5'N, long. 83º 5'W). The soil of the Watkinsville, GA, USA location is a Cecil sandy clay loam series (0% to 2% slope) while the Tifton, GA, USA location was a Tifton loamy sand series (2% to 5% slope) (USDA, 2022). Approximately 20 kg of soil was collected from each location (0-15 cm depth) and passed through a 4-mm sieve. Soil samples were stored in 5-gallon buckets at field water content and kept aerated at room temperature before the incubation (Cabrera, 1993).

The maximum water holding capacity (WHC) was estimated through saturation and draining over a sand bath for 48 h (Priha & Smolander, 1999) and averaged 0.25g $H_2O{\cdot}g^{-1}$ soil and 0.30g $H_2O{\cdot}g^{-1}$ soil for the Tifton and Cecil soils, respectively. Soils were analyzed for total N, total C, phosphorous (P), potassium (K), magnesium (Mg), and calcium (Ca) concentrations, pH, buffer ph (pHb) and cation exchange capacity (CEC) by the UGA Agriculture and Environmental Services Laboratory (UGA AESL) (University of Georgia, Athens, GA, USA) (Table 6.1) (Kissel and Vendrell, 2012; Kissel and Sonon, 2011).

Table 6.1. Initial characteristics of the Cecil sandy clay loam (Cecil) and the Tifton loamy sand (Tifton) soils used in the study.

Soil	Total N	Total C	P	K	Mg	Ca	pHw[i]	pHb[i]	CEC[i]
	mg·kg^{-1} dry soil								
Cecil	3,100	17,900	33.5	116.5	63.5	677	5.5	7.7	7.0
Tifton	2,100	11,000	39.5	38.0	30.5	320	5.4	7.7	4.3

[i]Water pH=pHw measured using a 1:1 water:soil mixture, buffer pH = pHb, which is measured using a 1:1 mixture of soil and 0.01 M calcium chloride, Cation Exchange Capacity = CEC.

Three commercial fertilizers, a mixed organic fertilizer (MIX) (10N-0.88P-6.6K; All Season Organic Fertilizer; Nature Safe, Irving, TX, USA) composed of feather-meat-bone-blood meal, and a pelleted poultry litter (PPL) (5N-1.8P-2.5K; Harmony Organic Fertilizer; Environmental Products LLC, Roanoke, VA, US), and feather meal (FM) (13N-0P-0K; Mason City By-Products, Mason City, Iowa, USA) were sourced from a commercial supply company (7 Springs Farm Supply, Check, VA, USA). Total N, C, NO_3, and NH_4 of the three organic fertilizers were determined by the UGA AESL (University of Georgia, Athens, GA, USA) (Table 6.2) (Kissel and Sonon, 2011).

Table 6.2. Characteristics of feather meal (FM), pelleted poultry litter (PPL) and mixed source (MIX) organic fertilizers used in the incubation study.

Material	Total N	NO_3-N	NH_4-N	Inorganic N	Total C	C:N ratio
	%					
FM	13.61	0.85	0.33	1.18	48.17	3.54
PPL	4.36	0.90	0.14	1.04	27.74	6.36
MIX	9.44	0.35	0.14	0.49	34.35	3.64

Laboratory incubation study

To determine the rate of mineralization from the three organic fertilizers, a soil incubation study was performed for 120 d. Soil was rewetted to 50% of estimated maximum WHC and allowed to pre-incubate under aerobic conditions for 48 h to mitigate the initial flux mineralization that typically occurs during soil rewetting (Cabrera, 1993). Organic fertilizers were applied at a rate to supply 100 mg $N\cdot kg^{-1}$ to soils at 50% WHC. The organic fertilizers were added to 300 g dry equivalent soil in resealable polyethylene bags (1 Quart Ziploc Freezer Bag, SC Johnson, Racine, WI, USA) and mixed thoroughly. Storage bags were incubated at 4, 10, 20, and 30°C for

120 d (Cassity-Duffey et al., 2017). The bags were aerated, and water content was maintained gravimetrically every 2 to-3 d. To determine the rate of release of inorganic N over time, 5 g subsamples of soil were taken at 0, 2, 4, 7, 14, 35, 56, 85, and 120 d and were extracted with 40 ml 1 M KCl, shaken for 30 min and passed through filter paper (Whatman 42, Maidstone, Kent, UK). Prior to sub-sampling, soils were thoroughly mixed to avoid sampling heavily concentrated areas of fertilizers. Inorganic N was determined colorimetrically (Crooke & Simpson, 1971; Keeney & Nelson, 1982).

Mineralization kinetics and statistics

Cumulative Net N mineralized was calculated for the control soils (unamended), where:

$$\text{Control Net } N_{\text{min}} = \text{Inorganic } N_{t=x} \text{-Inorganic N Control}_{t=0} \tag{6.1}$$

Cumulative Net N mineralized (Net N_{min}) from the materials was calculated, where:

$$\text{Net } N_{\text{min}} = \text{Inorganic } N_{t=x} \text{-Inorganic N Control}_{t=x} \text{-Inorganic N of Material}_{t=0} \tag{6.2}$$

Net N_{min} was expressed as mg inorganic $N \cdot kg^{-1}$ dry material and as a percentage of total N from each applied fertilizer. The Net N_{min} values for each incubation time were analyzed using the ANOVA method by least-squares fit using JMP Pro 16.0 (SAS Institute Inc., Cary, NC). Soil type, fertilizer treatment and temperature were treated as fixed effects, and replication was treated as a random effect. When statistically significant differences existed according to ANOVA ($P<0.05$), mean separation was performed with Tukey's test at $\alpha = 0.05$.

To determine the N mineralization kinetics the Net N_{min} (mg inorganic $N \cdot kg^{-1}$ dry material) was fit to first-order kinetics using non-linear model:

$$\text{Net } N_{\text{min}} = N_0[1 - e^{-kt}] \tag{6.3}$$

where N_0 is the potentially mineralizable N, k is the rate coefficient of net N mineralization (mg inorganic N $\cdot kg^{-1} \cdot d^{-1}$), and t is time (days of incubation) (Cabrera et al., 2008). The values of linear fit were determined (Table 6.3). The iterations for N_0 and k calculations, and curve fitting of equations were carried out using a non-linear method with G-Newton iteration using JMP Pro 16.0 (SAS Institute Inc., Cary, NC). The performance of the fit was evaluated using the root mean squared error (RMSE), RMSE-observations standard deviation ratio (RSR), Nash-Sutcliffe efficiency (NSE) and Percent bias (PBias). The RMSE is a commonly used error index statistic that quantifies the average magnitude of errors between predicted and observed values (Moriasi et al., 2007). A lower RMSE indicates a better model fit:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \tag{6.4}$$

The RSR is another way to assess the goodness of fit. The RSR standardizes RMSE by considering the standard deviation of the observed data (Moriasi et al., 2007).

The NSE assesses the deviation between model predictions and observed values relative to the scattering of the observed data (Moriasi et al., 2007). It ranges from negative infinity to 1, where an NSE of 1 indicates a perfect fit:

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right] \tag{6.5}$$

The PBias quantifies the systematic error or bias in a model's predictions by calculating the average difference between predicted and observed values. If the model underestimates, on average, the PBias is positive; conversely, if the model overestimates, on the average, the PBias is negative:

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2 * (100)}{\sum_{i=1}^{n}(O_i)}\right] \tag{6.6}$$

The residual sum of squares of analysis (RSS) was used to determine significant model differences (Miliken & Debruin, 1978). For example, when evaluating whether the rate constant

(k) values for the mineralization of FM differed between two specific soils (Ho: k values are the same), the first-order model was fit using their individual N_0 values but a single k value. The sum of squares residual of that model constituted the sum of squares residual under Ho (SSresHo). Combining the sum of squares residuals from models fitted to each of the two soils individually constituted the sums of squares residual for using individual models with different N_0 and k values (SSres). The sum of squares residual due to deviation from Ho was calculated as:

$$\mathrm{SS_{dev}Ho = SS_{res}Ho - SS_{res}} \qquad (6.7)$$

Subsequently, an F value was calculated as:

$$\mathrm{F} = \frac{\left(\mathrm{SS_{dev}Ho}/\mathrm{df}\right)}{\left(\mathrm{SS_{res}}/\mathrm{df}\right)} \qquad (6.8)$$

Where df refers to the corresponding degrees of freedom. If the computed F value > F (df numerator, df denominator, $\alpha = 0.05$) from the F table, Ho was rejected, indicating that k values were not equal.

Results & Discussion

Laboratory incubation

There was a linear correlation between incubation time and Net N_{min} in the control soils (Figure 6.1). Net N_{min} was significantly higher in the Cecil series soil compared to the Tifton series soil, which is likely to be related to the higher organic matter content compared to the Tifton soil. In both soils, the Net N_{min} was significantly higher when incubated at 30°C, while minimal differences were observed in Net N_{min} at 4, 10, and 20°C.

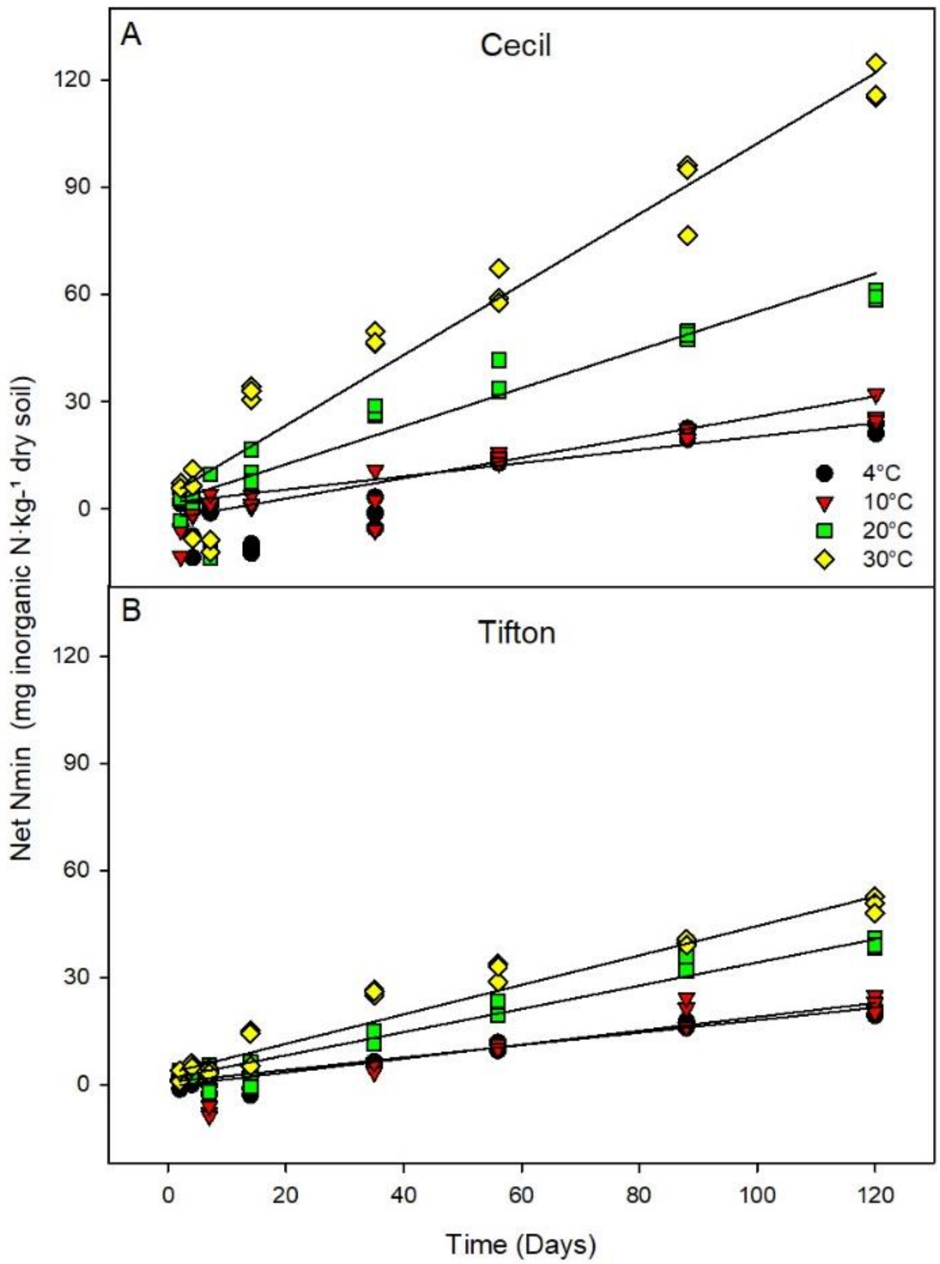

Figure 6.6. Net N mineralization (% of total N applied) from Cecil (A) and Tifton (B) soils at 4, 10, 20 and 30 °C over 120 d of incubation.

Beginning at 35 d, there was a trend of consistent significant differences among treatment combinations, leading to the decision to present data only from 2, 4, 7, 14, 35, and 120 d of incubation (leaving out 57 and 85 d of incubation) for both Tifton and Cecil soils with different combinations of fertilizer and temperature treatments. There were significant interactions between soil series, fertilizer type, and incubation temperature on the Net N_{min} at various time points over the 120 d period (Tables 6.3, 6.4). In the Cecil series soil, differences of Net N_{min} between combinations of fertilizer and temperature were evident within the first 4 d of incubation (Table 6.3). The FM had a higher Net N_{min} among materials incubated at 20 and 30 ^{o}C compared to 4 and 10 ^{o}C from 4 d and continuing to 35 d of incubation (Table 6.3). In contrast, minimal effects of temperatures were observed with MIX and PPL fertilizers in the first 35 d of incubation, with the exception of the PPL fertilizer at 14 d, where the PPL had 0% Net N_{min} at 30 °C, which was less than the 9% observed at 4 d. In the Cecil soil, results suggest that high temperatures may have impacted the Net N_{min} immediately after application for the FM but less for the other fertilizers, which might have favored the occurrence of alternative processes other than mineralization (Hadas et al., 1983). At 120 d of incubation, the temperature did not affect Net N_{min} of FM or PPL but did impact Net N_{min} of the MIX fertilizer in the Cecil soil. Net N_{min} of MIX fertilizer was greater at 20°C (62%) than Net N mineralization at 10°C (38%). These findings align with previous results reported by Lazicki et al. (2019), which suggest that temperature has a more considerable impact during the first few days after incorporation of organic fertilizers but has less of an impact on N mineralization after a long period (Lazicki et al., 2019).

Table 6.3. Net N mineralized (Net N_{min}[i]) from the feather meal (FM), mixed source (MIX), and pelleted poultry litter (PPL) fertilizers incubated at 4, 10, 20 and 30 °C for 120 d in a Cecil sandy clay loam soil.

Time of incubation (Days)	Fertilizer	Temperature			
		4°C	10°C	20°C	30°C
		Net N_{min} (%)			
2	FM	0.54 A a[ii]	3.55 A a	3.50 A a	0.00 A a
	MIX	0.00 A a	4.87 A a	2.10 A a	0.00 A a
	PPL	0.00 A a	0.00 A a	4.81 A a	2.03 A a

	FM	11.76	AB ab	5.90	A b	21.03	A ab	32.56	A a
4	MIX	6.37	B ab	2.20	A b	3.26	C b	10.30	AB a
	PPL	19.40	A a	1.50	A a	11.65	B a	6.25	B a
	FM	30.41	A c	39.80	A b	51.30	A a	43.20	A ab
14	MIX	20.00	A a	-		28.27	B a	17.90	B a
	PPL	18.00	A a	13.73	B a	12.70	C a	0.00	C b
	FM	59.20	A b	56.25	A b	62.50	A ab	68.81	A a
35	MIX	34.61	B a	31.16	B a	32.00	B a	34.30	B a
	PPL	27.07	C a	23.76	B a	15.44	C a	13.22	C a
	FM	62.30	A a	57.82	A a	70.40	A a	68.91	A a
120	MIX	43.74	B ab	38.40	B b	62.34	A a	43.10	B ab
	PPL	19.67	C a	25.76	C a	21.20	B a	17.17	C a

[i]Net N_{min}=Inorganic $N_{d=x}$-Inorganic N $Control_{t=x}$-Inorganic N of $Material_{t=0}$

[ii]Different uppercase letters represent significant differences within columns of fertilizers at each sampling point, and different lowercase letters represent significant differences among different temperatures for each fertilizer and incubation time according to Tukey's honest significant difference test (P<0.05).

Feather meal is derived from *hydrolyzed, dried, and ground poultry feathers*, and during mineralization, long chains of keratin molecules are cleaved into smaller and more accessible components, which may enhance N release after relatively short incubation times (Hadas & Kautsky 1994; Jan et al. 2009). Conversely, MIX and PPL have previously been shown to have slower mineralization than FM when incubated at 30 ^{o}C (Cassity-Duffey et al. 2019) However, PPL fertilizer had relatively low N available, which might be due to factors like the presence of bedding materials, moisture content, and processing (Hadas et al., 1983). The processing of the poultry product can involve drying, grinding, and compressing the material into uniform pellets, which can affect the availability and release of N (Hadas et al., 1983; Mazeika et al., 2016; Purnomo et al., 2017)

The effect of temperature on Net N_{min} of different fertilizers in Tifton soil was variable at different time points (Table 6.4). After 4 d of incubation, the FM fertilizer had a significantly greater Net N_{min} at 20 and 30 °C (14% and 18%, respectively) than at 4 and 10 °C (2% and 0%). However, as time progressed, Net N_{min} for the FM was greater at lower temperatures by 35 d of incubation. Temperature had a lesser impact on the Net N_{min} of MIX throughout the incubation period, with the greatest Net N_{min} occurring at 20 °C after 120 d. The Net N_{min} of PPL in the Tifton soil did not respond in the same way as FM to higher temperatures, with a complete absence of Net N_{min} at 30 °C starting from 14 d until 120 d, suggesting that higher temperatures favored the occurrence of other N processes in the PPL fertilizer instead of mineralization.

Table 6.4. Net N mineralized (Net N_{min}^{i}) from the feather meal (FM), mixed source (MIX), and pelleted poultry litter (PPL) fertilizers incubated at 4, 10, 20 and 30 °C for 120 d in a Tifton loamy sand soil.

Time of incubation (Days)	Fertilizer	Temperature 4°C		10°C		20°C		30°C	
		Net N_{min} (%)							
2	FM	3.01	A a	3.35	A a	3.23	A a	3.96	B a
	MIX	0.25	A b	3.50	A ab	0.00	A b	4.26	B a
	PPL	3.17	A ab	0.00	A b	5.66	A ab	12.90	A a
4	FM	1.80	A bc	0.00	B c	13.81	A ab	17.76	A a
	MIX	1.21	A a	1.16	B a	0.96	B a	4.65	A a
	PPL	2.56	A b	11.06	A ab	15.20	A a	9.83	A ab
14	FM	26.80	A a	27.40	A a	42.04	A a	32.30	A a
	MIX	6.40	B a	9.74	B a	23.00	AB a	18.94	AB a
	PPL	17.43	AB a	9.11	B ab	8.00	B ab	0.00	B b
35	FM	48.47	A ab	54.00	A a	46.74	A ab	41.45	A b
	MIX	21.51	B a	30.43	B a	32.44	A a	37.61	A a
	PPL	12.66	C a	17.58	C a	3.53	B b	0.00	B b
120	FM	59.14	A a	61.66	A a	52.42	A b	40.24	A b

MIX	30.11	B b	33.42	B b	47.85	A a	27.80	A b
PPL	15.15	C a	11.16	C a	12.34	B a	0.00	B a

[i]Net N_{min}=Inorganic $N_{d=x}$-Inorganic N $Control_{t=x}$-Inorganic N of $Material_{t=0}$

[ii]Different uppercase letters represent significant differences within columns of fertilizers at each sampling point, and different lowercase letters represent significant differences among various temperatures for each fertilizer and incubation time according to Tukey's honest significant difference test (P<0.05).

Our results suggest potential N loss mechanisms from fertilizers during incubation, such as NH_3 volatilization or N immobilization, which are likely to be favored by high temperatures (Hadas et al., 1983). Losses during early incubation periods from FM in the Cecil soil may be the result of a pattern of quick net immobilization followed by gradual mineralization, which reflects the dynamic nature of microbial activity in response to the changing availability of labile carbon compounds in the substrate (Lazicki et al., 2020; Quan et al., 2021). In contrast, it is possible that NH_3 volatilization occurred in the PPL at 30 °C. However, temperature is just one factor influencing NH_3 volatilization (Cabrera et al., 1993; Hargrove, 1988). Soil properties such as moisture, pH, CEC, and organic matter content also play a role (Hadas et al., 1983; Zhenghu & Honglang, 2000). In this context, NH_3 volatilization may be more likely to occur in the Tifton soil than the Cecil soil due to its relatively high pH, low organic matter, and high sand content (Wang & Alva, 2000).

Mineralization kinetics

A first-order model was fitted to NET inorganic N concentration during the 120 d incubation for each soil, fertilizer, and temperature treatment (Table 6.5, Figure 6.2). The potentially mineralizable N, N0, K, RMSE, RSR, NSE, and PBias were determined for each treatment combination.

Table 6.5. Linear fitting characteristics of the data for Cecil sandy clay loam (Cecil) and Tifton loamy sand (Tifton) soils, feather meal (FM), pelleted poultry litter (PPL), and mixed source (MIX) organic fertilizers and incubation temperatures for Net nitrogen (N) (NH_4–N + NO_3–N) mineralized over 120 days.

Soil	Fertilizer	Incubation Temp.	Mineralized N measured at 120 d	N0	First-order rate coefficient	RMSE	RSR	NSE	PBIAS
		°C	mg inorganic N·kg^{-1} dry soil						
Cecil	FM	4	65.22	64.54	0.04	4.64	0.26	0.93	1.42
		10	60.53	62.75	0.07	4.39	0.26	0.93	-5.52
		20	73.70	65.12	0.10	13.46	0.72	0.49	-15.47
		30	72.14	79.89	0.08	11.10	0.50	0.75	-4.83
	PPL	4	17.15	17.17	0.26	5.14	0.85	0.28	-11.74
		10	22.46	19.21	0.09	4.46	0.73	0.46	-24.97
		20	18.48	8.38	0.84	4.15	0.97	0.06	35.48
		30	14.98	15.04	0.03	8.21	0.82	0.33	-1.55
	MIX	4	41.29	38.01	0.04	4.59	0.36	0.87	-8.84
		10	36.24	37.41	0.03	4.70	0.41	0.83	-12.30
		20	58.85	55.57	0.03	6.14	0.35	0.88	-0.70
		30	40.67	46.31	0.04	6.23	0.39	0.85	-6.91
Tifton	FM	4	61.91	64.54	0.04	5.56	0.22	0.95	-2.98
		10	64.55	62.55	0.04	5.21	0.25	0.94	-6.00
		20	50.09	48.03	0.11	5.55	0.33	0.89	-2.06
		30	42.13	41.85	0.10	7.14	0.51	0.74	-3.77
	PPL	4	13.22	12.28	0.29	5.60	0.87	0.25	-2.32
		10	9.74	10.56	0.22	4.13	0.80	0.36	-5.90
		20	10.76	8.38	0.84	8.95	1.00	0.01	-0.27
		30	0	-	-	-	-	-	-

MIX	4	28.43	32.72	0.02	3.25	0.26	0.93	-5.42
	10	31.55	30.61	0.03	4.82	0.38	0.86	-4.79
	20	49.49	48.93	0.03	7.85	0.41	0.83	-1.90
	30	26.24	30.15	0.09	8.39	0.64	0.59	-1.23

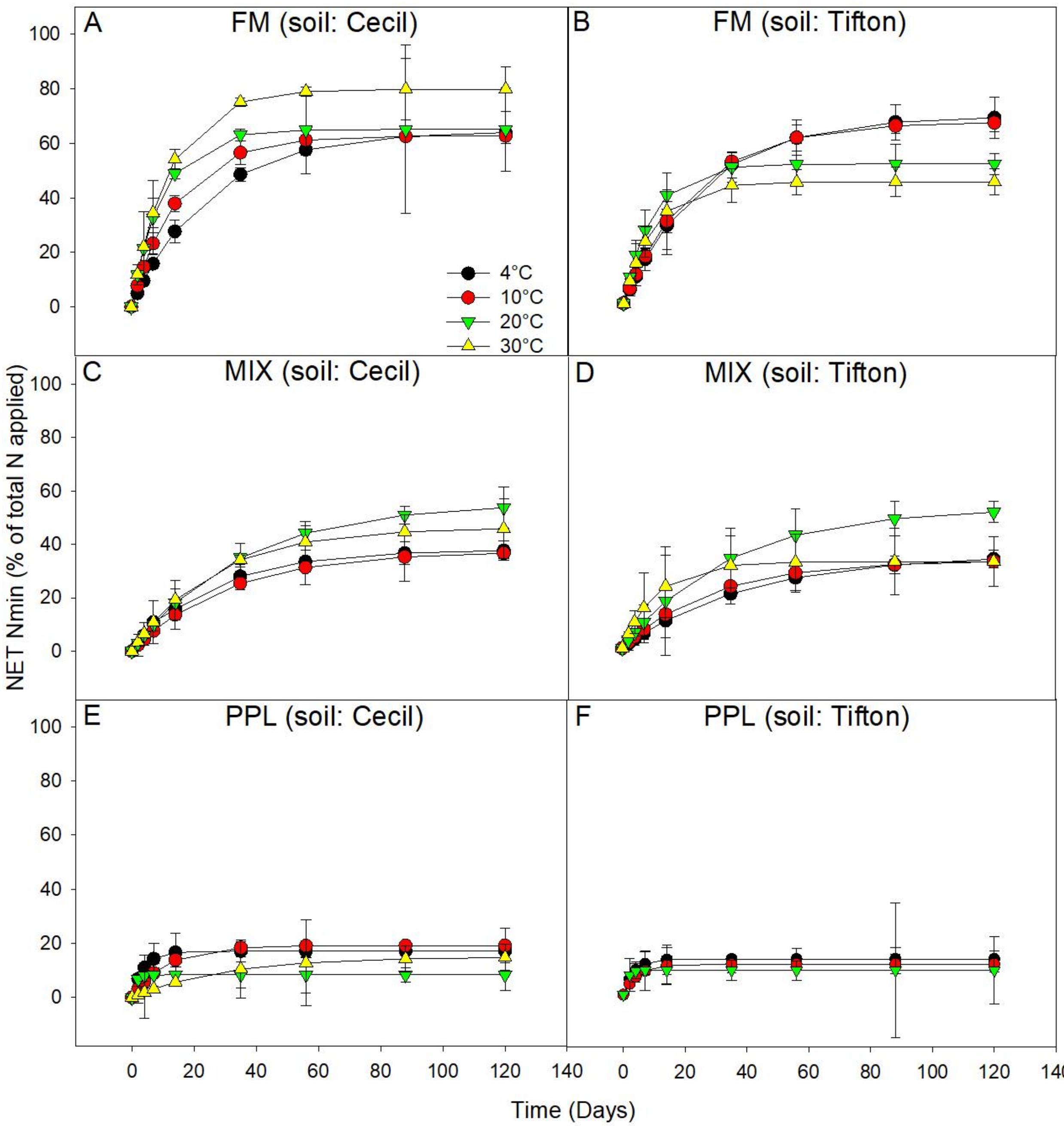

Figure 6.7. Net N mineralization (% of total N applied) from the FM, MIX and PPL fertilizers incubated at 4, 10, 20, and 30 °C for 120 d in Cecil and Tifton soils and associated first order regressions (error bars indicated standard deviations).

The first-order kinetic model fits varied with different treatment combinations. The model demonstrated good efficiency in predicting the N mineralization of the FM fertilizer under most temperature and soil conditions, with NSE values ranging from 0.74 to 0.95 and RSR values between 0.22 and 0.51. There was an exception for modeling the FM fertilizer in Cecil soil at 20°C, where the NSE value dropped below 0.50 and RSR exceeded 0.70, suggesting a weaker correlation between observed and predicted values. In this specific fit, there was a tendency for the model to overestimate N mineralization, resulting in a negative Pbias of -15.47. In contrast, the model efficiency for predicting the N mineralization of MIX was satisfactory and consistent across different soil and temperature combinations, with NSE values ranging from 0.59 to 0.93 and RSR values between 0.26 and 0.64.

The model's performance was unsatisfactory for predicting the N mineralization of PPL fertilizer. In all first-order kinetic fits RSR values exceeded 0.70, which may be attributed to the considerable variability in Net N_{min} observed among the samples of this material during the 120 d incubation (Table 6.4 and 6.5). This variability negatively affected the correlation between observed and predicted values, which also resulted in NSE values between 0.06 and 0.46. Furthermore, the PBIAS of the models predicting harmony ranged from a positive value of 35.48 to negative values as low as -11.74, which indicates a tendency of both under and overestimation of model simulation.

Effect of soil texture and temperature on Net N mineralization and model fit

The pairwise residual sums of squares (RSS) analysis indicated that k and N_0 values were different among temperatures in all soil and fertilizer treatments (data not shown), which indicates that individual models are necessary to describe Net N_{min} from MIX, PPL and FM in different soils and temperatures. The interactions between soil and temperature are necessary for understanding the patterns of N mineralization of different organic fertilizers. In a previous study, Lazicki et al. (2019) observed variability for potentially crop-available N among 22 different organic materials trialed under warm and moist conditions (23°C and 60% water holding capacity), with some undergoing N immobilization while others released up to 90% of applied N. The authors suggested, while the Net N_{min} was well correlated with the C:N ratio of each material, the soil texture and management history of the soils influenced the timing of N release (Lazicki et al., 2019). Different soil attributes, such as pH, texture, organic matter, and cation exchange capacity (CEC), create distinct physical and chemical environments for microorganisms, which may influence when and how quickly microorganisms decompose organic N compounds (Lazicki et al., 2019). Furthermore, the degree of which the temperature can influence microbial growth and, consequently, the N mineralization rate is likely to vary across different environmental systems (Guntiñas et al., 2012).

FM fertilizer

The Net N_{min} predicted at 120 d for FM ranged from 60% to 80% of the total organic N applied in the Cecil soil (Figure 2A), and from 40% to 60% of the total organic N applied in the Tifton soil (Figure 2B). Similar Net N_{min} values have been previously reported for FM (Cassity-Duffey et al., 2020; Geisseler et al., 2021; Lazicki et al., 2019). In the present study, Net N_{min} of FM over the 120-d incubation in the Cecil soil showed two distinct phases: a rapid release during the first 14 d of incubation, a slow-release phase, and a plateau at approximately 80 d. In the Tifton soil, a similar pattern of rapid release occurred during the early stages of incubation followed by a steady and slow release at the temperatures of 4 and 10°C.At 20 and 30°C the rapid phase was followed by a plateau at approximately 35 d. In our model, the Net N_{min} of FM after 35 d ranged between 48% to 75% of total N in the Cecil soil, and between 40% to 48% of total N in the Tifton soil. The rapid mineralization observed from FM fertilizer in the 14 d of incubation corresponds to previous reports (Cassity-Duffey et al., 2020; Hartz and Johnstone, 2006), and may be attributed to the presence of readily available N-containing compounds, such as urea and simple organic forms of N that can be easily broken down by soil enzymes, even at lower temperatures. In contrast, the considerably slower N mineralization after 14 d indicates the predominance of microbial degradation of complex organic N forms (Hartz and Johnstone, 2006). A model proposed by Geisseler et al. (2021) predicted that 61% of total N from FM would be in the mineral form after 100 d of incubation, with half of that being in the mineral form after only 5 d of incorporation.

In the Cecil series soil models, the k and N_0 values were not significantly different among temperatures, with constant k values ranging between 0.04 and 0.10 and N_0 values between 62.75 and 79.89 (Table 6.5). In contrast, in the Tifton soil the N_0 rates were greater at the lower temperatures (4°C and 10°C), suggesting that temperature might affect N mineralization of FM in the Tifton soil to a greater degree compared with Cecil soil. Our results for FM in the two soils agrees with results reported by Dessurealt-Rompré et al. (2010), that sandy loam soils had a greater response of soil N mineralization rate to changes in temperature compared with predominately clay soils. Additionally, the analysis of variance showed that k and N_0 values were not significantly different between soils, with the only exception with the highest temperature of 30 ^{o}C (data not shown), suggesting that overall differences for the rate of mineralization and potentially mineralizable N of FM in different mineral soils may be minimal at lower temperatures.

MIX fertilizer

The Net N_{min} predicted for the MIX fertilizer in the Cecil and Tifton soils after 120 d ranged between 35% to 55% and 30% to 45% of total organic N applied, respectively (Figures 6.2C, 6.2D). The N release throughout the 120-d incubation steadily increased but at a lower rate after 35 d, except when incubated at 30°C in the Tifton series soil, where a plateau phase was observed at around 35 d. In a previous study, Cassity-Duffey et al., (2020b) investigated the nitrogen mineralization of organic fertilizers across four distinct soils over a 100-d incubation period. Their findings revealed that most of N mineralized from a pelletized MIX fertilizer, composed of animal meals, occurred within the initial two weeks of incubation, with approximately 53% to 58% of the initially applied nitrogen mineralized after 14 days (Cassity-Duffey et al., 2020b).

The model fits for MIX fertilizer had rate *k* values between 0.02 and 0.09, while N_0 values ranged between 30.61 and 55.57 (Table 6.5). The analysis of variance showed that *k* and N_0 values for the MIX product were not significantly different between soil types or incubation temperatures (data not shown). Accordingly, we may expect minimal differences between the two soils for the N release of MIX fertilizer. Cassity-Duffey et al. (2020b) also reported no significant effects of soil texture between Cecil and Tifton soils on the Net N_{min} of a pelletized MIX fertilizer. Interestingly, their research suggested that pH levels may be more influential than soil clay content in determining the potential N mineralization (Cassity-Duffey et al. 2020b).

PPL Fertilizer

The Net N_{min} predicted for the PPL fertilizer after 120 d was less than 20% of total N applied, regardless of soil type or temperature (Figures 6.2E, 6.2F). The model fits for soils and temperature combinations showed most N release during the first few days of incubation, followed by a plateau after the second week. On average, 10% of total N applied is predicted to be available from PPL after 7 d of incubation. Previous studies predicting N release from PPL reported higher values, with potential available N ranging between 25% to 50% of applied N (Cassity-Duffey et al., 2020; Hadas et al.; 1983); with most of the N released during the initial 7 d of incubation.

Model fits of the PPL product had a wide variability of *k* rates, with values ranging between 0.03 and 0.84 among treatments of soil and temperatures (Table 5). In contrast, N_0 values ranged between 8.38 and 19.21 and no significant differences were observed among treatments of soils and temperatures (data not shown). Our results for PPL mineralization agrees with other studies evaluating the N mineralization of organic fertilizers, which suggest that temperature affects *k* rate more than the mineralization potential N_0 (Griffin & Honeycutt, 2000; Lazicki et al., 2019). Thus, changes on N mineralization of PPL in response to environmental conditions are likely minimal.

Conclusion

The study investigated N mineralization from three organic fertilizers in two distinct soil classes and several temperatures encountered during vegetable production. The Net N_{min} varied with soil, fertilizer type, and temperature, indicating that accurately predicting N mineralization from organic fertilizers may be specific for individual farms and fertilizer sources. In general, the models demonstrated good efficiency in predicting the N mineralization of FM and MIX fertilizers but were inefficient for predicting N mineralization of PPL. After 120 d, Net N_{min} from FM fertilizer ranged between 42% to 72%, followed by the MIX fertilizer (26% to 59% Net N_{min}), while a lower Net N_{min} was observed with the PPL fertilizer (0% to 22%). Temperature and soil type had a relatively minor impact on the potentially mineralizable N of the MIX and PPL fertilizers at 120 d. However, incubation at higher temperatures (20°C and 30°C) impacted Net N_{min} of FM fertilizer in the Tifton series soil. Temperature-related differences may not be substantial enough to influence a grower's decisions regarding N fertilizer inputs for vegetable crop production in the two soils. However, organic fertilizer source will likely play a significant role in N availability during the cropping season.

References

Agehara, S., & Warncke, D. D. (2005). Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. *Soil Science Society of America Journal*, *69*(6), 1844-1855. https://doi.org/10.2136/sssaj2004.0361

Bergstrand, K. J. (2022). Organic fertilizers in greenhouse production systems–a review. *Scientia Horticulturae*, *295*, 110855. https://doi.org/10.1016/j.scienta.2021.110855

Bowles, T. M., Acosta-Martínez, V., Calderón, F., & Jackson, L. E. (2014). Soil enzyme activities, microbial communities, and carbon and nitrogen availability in organic agroecosystems across an intensively managed agricultural landscape. *Soil Biology and Biochemistry*, *68*, 252-262. https://doi.org/10.1016/j.soilbio.2013.10.004

Cabrera, M. L. (1993). Modeling the flush of nitrogen mineralization caused by drying and rewetting soils. *Soil Science Society of America Journal*, *57*(1), 63-66. https://doi.org/10.2136/sssaj1993.03615995005700010012x

Cabrera, M., Molina, J. A., & Vigil, M. (2008). Modeling the nitrogen cycle. In: Schepers, J. S., & Raun, W. (eds.). *Nitrogen in agricultural systems* (pp. 695-730). ASA. Madison, WI.

Cabrera, M. L., Chiang, S. C., Merka, W. C., Thompson, S. A., & Pancorbo, O. C. (1993). Nitrogen transformations in surface-applied poultry litter: Effect of litter physical characteristics. *Soil Science Society of America Journal*, *57*(6), 1519-1525. https://doi.org/10.2136/sssaj1993.03615995005700060021x

Cabrera, M. L., & Kissel, D. E. (1988). Evaluation of a method to predict nitrogen mineralized from soil organic matter under field conditions. *Soil Science Society of America Journal*, *52*(4), 1027-1031. https://doi.org/10.2136/sssaj1988.03615995005200040024x

Cabrera, M. L., Kissel, D. E., & Vigil, M. F. (2005). Nitrogen mineralization from organic residues: Research opportunities. *Journal of environmental quality*, *34*(1), 75-79. https://doi.org/10.2134/jeq2005.0075

Calderón, F. J., McCarty, G. W., Van Kessel, J. A. S., & Reeves III, J. B. (2004). Carbon and nitrogen dynamics during incubation of manured soil. *Soil Science Society of America Journal*, *68*(5), 1592-1599. https://doi.org/10.2136/sssaj2004.1592

Cassity-Duffey, K. B., Moore, A., Satterwhite, M., & Leytem, A. (2018). Nitrogen mineralization as affected by temperature in calcareous soils receiving repeated applications of dairy manure. *Soil Science Society of America Journal*, *82*(1), 235-242. https://doi.org/10.2136/sssaj2017.02.0044

Cassity-Duffey, K., Cabrera, M., Gaskin, J., Franklin, D., Kissel, D., & Saha, U. (2020a). Nitrogen mineralization from organic materials and fertilizers: Predicting N release. *Soil Science Society of America Journal*, *84*, 522–533. https://doi.org/10.1002/saj2.20037

Cassity-Duffey, K., Cabrera, M., Franklin, D., Gaskin, J., & Kissel, D. (2020b). Effect of soil texture on nitrogen mineralization from organic fertilizers in four common southeastern soils. *Soil Science Society of America Journal*, *84*(2), 534-542. https://doi.org/10.1002/saj2.20039

Crooke, W. M., & Simpson, W. E. (1971). Determination of ammonium on Kjeldahl digests of crops by an automated procedure. *Journal of the Science of Food and Agriculture*, *22*, 9–10. https://doi.org/10.1002/jsfa.2740220104

De Neve, S., & Hofman, G. (1998). N mineralization and nitrate leaching from vegetable crop residues under field conditions: a model evaluation. *Soil Biology and Biochemistry*, *30*(14), 2067-2075. https://doi.org/10.1016/S0038-0717(98)00082-0

Dessureault-Rompré, J., Zebarth, B. J., Georgallas, A., Burton, D. L., Grant, C. A., & Drury, C. F. (2010). Temperature dependence of soil nitrogen mineralization rate: Comparison of mathematical models, reference temperatures and origin of the soils. *Geoderma*, *157*(3-4), 97-108. https://doi.org/10.1016/j.geoderma.2010.04.001

Gale, E.S., Sullivan, D.M., Cogger, C.G., Bary, A.I., Hemphill, D.D., & Myhre, E.A. (2006). Estimating plant-available nitrogen release from manures, composts, and specialty products. *Journal of Environmental Quality, 35,* 2321-2332. https://doi.org/10.2134/jeq2006.0062

Geisseler, D., Horwath, W. R., Joergensen, R. G., & Ludwig, B. (2010). Pathways of nitrogen utilization by soil microorganisms–a review. *Soil Biology and Biochemistry*, *42*(12), 2058-2067. http://dx.doi.org/10.1016/j.soilbio.2010.08.021

Geisseler, D., Smith, R., Cahn, M., & Muramoto, J. (2021). Nitrogen mineralization from organic fertilizers and composts: Literature survey and model fitting. *Journal of Environmental Quality*, *50*(6), 1325-1338. https://doi.org/10.1002/jeq2.20295

Griffin, T. S., & Honeycutt, C. W. (2000). Using growing degree days to predict nitrogen availability from livestock manures. *Soil Science Society of America Journal, 64,* 1876–1882. https://doi.org/10.2136/sssaj2000.6451876x

Gonçalves, J. L. D. M., & Carlyle, J. C. (1994). Modelling the influence of moisture and temperature on net nitrogen mineralization in a forested sandy soil. *Soil Biology and Biochemistry*, *26*(11), 1557-1564. https://doi.org/10.1016/0038-0717(94)90098-1

Gordillo, R. M., & Cabrera, M. L. (1997). *Mineralizable nitrogen in broiler litter: II. Effect of selected soil characteristics* (Vol. 26, No. 6, pp. 1679-1686). American Society of

Agronomy, Crop Science Society of America, and Soil Science Society of America. https://doi.org/10.2134/jeq1997.00472425002600060031x

Guntiñas, M. E., Leirós, M. C., Trasar-Cepeda, C., & Gil-Sotres, F. (2012). Effects of moisture and temperature on net soil nitrogen mineralization: A laboratory study. *European Journal of Soil Biology*, *48*, 73-80. https://doi.org/10.1016/j.ejsobi.2011.07.015

Hadas, A., Bar-Yosef, B., Davidov, S., & Sofer, M. (1983). Effect of pelleting, temperature, and soil type on mineral nitrogen release from poultry and dairy manures. *Soil Science Society of America Journal*, *47*(6), 1129-1133. https://doi.org/10.2136/sssaj1983.03615995004700060014x

Hadas, A., & Kautsky, L. (1994). Feather meal, a semi-slow-release nitrogen fertilizer for organic farming. *Fertilizer research*, *38*, 165-170. https://doi.org/10.1007/BF00748776

Hargrove, W. L. (1988). Evaluation of ammonia volatilization in the field. *Journal of production agriculture*, *1*(2), 104-111. https://doi.org/10.2134/jpa1988.0104

Hassink, J., Bouwman, L. A., Zwart, K. B., Bloem, J., & Brussaard, L. (1993). Relationships between soil texture, physical protection of organic matter, soil biota, and C and N mineralization in grassland soils. In: Brussaard, L., & Kooistra, M. J. (eds.). *Soil Structure/Soil Biota Interrelationships* (pp. 105-128). Elsevier. https://doi.org/10.1016/B978-0-444-81490-6.50059-5

Hartz, T. K., & Johnstone, P. R. (2006). Nitrogen availability from high-nitrogen-containing organic fertilizers. *HortTechnology*, *16*(1), 39-42. https://doi.org/10.21273/HORTTECH.16.1.0039

Hartz, T. K., Smith, R., & Gaskell, M. (2010). Nitrogen availability from liquid organic fertilizers. *HortTechnology*, *20*(1), 169-172. https://doi.org/10.21273/HORTTECH.20.1.169

Honeycutt, C. W. (1999). Nitrogen mineralization from soil organic matter and crop residues: Field validation of laboratory predictions. *Soil Science Society of America Journal*, *63*(1), 134-141. https://doi.org/10.2136/sssaj1999.03615995006300010020x

Jan, M. T., Roberts, P., Tonheim, S. K., & Jones, D. L. (2009). Protein breakdown represents a major bottleneck in nitrogen cycling in grassland soils. *Soil Biology and Biochemistry*, *41*(11), 2272-2282. https://doi.org/10.1016/j.soilbio.2009.08.013

Kaupa, P., & Rao, B. R. (2014). Nitrogen mineralization and efficiency from co-applied animal manures and mineral fertilizer in sweetpotato under humid tropical conditions. *Field crops research*, *168*, 48-56. https://doi.org/10.1016/j.fcr.2014.08.011

Keeney, D. R. (1982). Nitrogen-Inorganic form. In Methods of soil analysis (part 2) Chemical and microbiological properties. *American Society of Agronomy*, 1159-643.

Kissel, D. E., & Sonon, L. S. (2011). Soil test handbook for Georgia. *University of Georgia Cooperative Extension Bulletin 62*.

Kissel, D. E., & Vendrell, P. F. Soil testing: Soil pH and salt concentration. *University of Georgia Cooperative Extension Circular 875*.

Knoepp, J. D., & Swank, W. T. (2002). Using soil temperature and moisture to predict forest soil nitrogen mineralization. *Biology and Fertility of Soils*, *36*, 177-182. https://doi.org/10.1007/s00374-002-0536-7

Lazicki, P., Geisseler, D., & Lloyd, M. (2019). Nitrogen mineralization from organic amendments is variable but predictable. *Journal of Environmental Quality*, *49*, 483–495. https://doi.org/10.1002/jeq2.20030

Lei, L., & McDonald, L. M. (2019). Soil moisture and temperature effects on nitrogen mineralization in a high tunnel farming system. *Communications in Soil Science and Plant Analysis*, *50*(17), 2140-2150. https://doi.org/10.1080/00103624.2019.1654503

Mazeika, R., Staugaitis, G., & Baltrusaitis, J. (2016). Engineered pelletized organo-mineral fertilizers (OMF) from poultry manure, diammonium phosphate and potassium chloride. *ACS Sustainable Chemistry & Engineering*, *4*(4), 2279-2285. https://doi.org/10.1021/acssuschemeng.5b01748

Miller, K. S., & Geisseler, D. (2018). Temperature sensitivity of nitrogen mineralization in agricultural soils. *Biology and Fertility of Soils*, *54*(7), 853-860. https://doi.org/10.1007/s00374-018-1309-2

Milliken, G. A., & Debruin, R. L. (1978). A procedure to test hypotheses for nonlinear models. *Communication in Statistics-Theory and Methods*, *7*, 65–79. https://doi.org/10.1080/03610927808827603

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885-900. https://doi.org/10.13031/2013.23153

Plante, A. F., & Parton, W. J. (2007). The dynamics of soil organic matter and nutrient cycling. In: Paul, E. (ed.). *Soil microbiology, ecology and biochemistry* (pp. 433-467). Academic Press. https://doi.org/10.1016/B978-0-08-047514-1.50020-2

Purnomo, C. W., Indarti, S., Wulandari, C., Hinode, H., & Nakasaki, K. (2017). Slow-release fertilizer production from poultry manure. *Chemical Engineering Transactions*, *56*, 1531-1536. https://doi.org/10.3303/CET1756256

Priha, O., & Smolander, A. (1999). Nitrogen transformations in soil under *Pinus sylvestris, Picea abies, and Betula pedula* at two forest sites. *Soil Biology and Biochemistry*, *31*, 965–977. https://doi.org/10.1016/S0038-0717(99)00006-1

Quan, Z., Huang, B., Lu, C., Su, C., Song, L., Zhao, X., ... & Fang, Y. (2021). Effects of ryegrass amendments on immobilization and mineralization of nitrogen in a plastic shed soil: A 15N tracer study. *Catena*, *203*, 105325. https://doi.org/10.1016/j.catena.2021.105325

Reganold, J. P., & Wachter, J. M. (2016). Organic agriculture in the twenty-first century. *Nature plants*, *2*(2), 1-8. https://doi.org/10.1038/nplants.2015.221

Sierra, J. (1997). Temperature and soil moisture dependence of N mineralization in intact soil cores. *Soil Biology and Biochemistry*, *29*(9-10), 1557-1563. https://doi.org/10.1016/S0038-0717(96)00288-X

Sims, J. T. (1986). *Nitrogen transformations in a poultry manure amended soil: Temperature and moisture effects* (Vol. 15, No. 1, pp. 59-63). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. https://doi.org/10.2134/jeq1986.00472425001500010014x

Soinne, H., Keskinen, R., Räty, M., Kanerva, S., Turtola, E., Kaseva, J., Nuutinen, V., Simojoki, A., & Salo, T. (2021). Soil organic carbon and clay content as deciding factors for net nitrogen mineralization and cereal yields in boreal mineral soils. *European Journal of Soil Science*, *72*(4), 1497-1512. https://doi.org/10.1111/ejss.13003

Stanford, G., & Smith, S. J. (1972). Nitrogen mineralization potentials of soils. *Soil Science Society of America Journal*, *36*(3), 465-472. https://doi.org/10.2136/sssaj1972.03615995003600030029x

US Department of Agriculture. (2022). Soil survey. Web soil survey – Soil survey of Oconee and Tift Counties, Georgia. https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx. (accessed 28 Mar 2023).

Van Veen, J. A., Ladd, J. N., & Amato, M. (1985). Turnover of carbon and nitrogen through the microbial biomass in a sandy loam and a clay soil incubated with [14C (U)] glucose and [15N](NH4) 2SO4 under different moisture regimes. *Soil Biology and Biochemistry*, *17*(6), 747-756. https://doi.org/10.1016/0038-0717(85)90128-2

Wang, F. L., & Alva, A. K. (2000). Ammonium adsorption and desorption in sandy soils. *Soil Science Society of America Journal*, *64*(5), 1669-1674. https://doi.org/10.2136/sssaj2000.6451669x

Wortman, S. E., Holmes, A. A., Miernicki, E., Knoche, K., & Pittelkow, C. M. (2017). First-season crop yield response to organic soil amendments: A meta-analysis. *Agronomy Journal*, *109*, 1210–1217. https://doi.org/10.2134/agronj2016.10.0627

Zhenghu, D., & Honglang, X. (2000). Effects of soil properties on ammonia volatilization. *Soil Science and Plant Nutrition*, *46*, 845–852. https://doi.org/10.1080/00380768.2000.10409150

CHAPTER 7

CONCLUSIONS

Onion (*Allium cepa* L.) generally has substantial nitrogen (N) requirements due to a shallow root system, long growing season, and high planting density. For short-day onions cultivated in the coastal plain of Georgia, USA, where sandy loam soils predominate, successful production relies on the implementation of N fertilization strategies that meet the nutritional needs of the crop to maximize yield and bulb quality. In the present dissertation, we conducted a series of studies to develop the information necessary for the optimization of the N fertilizer program of conventional and organic short-day onions in Georgia.

In chapter 3, we investigated the impact of the timing and rates of N fertilizer application on the yield and quality of conventionally-grown short-day onions in Georgia, USA. Our hypothesis was that applying N-fertilizer earlier during the bulb growth stage would enhance plant N uptake, reduce total nitrogen requirements, and mitigate quality issues associated associated with late-season N fertilizer applications. Our results indicate varying effects of fertilizer N rate on yield between the 2020 and 2021 growing seasons, likely due to differences in rainfall and subsequent soil mineral N accumulation. Excessive rainfall in 2020 reduced soil N availability, leading to yield increases at higher N application rates (135 lb/acre N). In 2021, with evenly distributed rainfall, yields were comparable across fertilizer N rate treatments. The timing of N fertilizer application, particularly at bulb initiation, improved onion bulb size and reduced pungency. In conclusion, short-day onions cultivated in Georgia may require 135 lb/acre N or more during years with high levels of precipitation, while in years with less rainfall, N rates as low as 75 lb/acre N may result in yields that are comparable to onions grown with up to 135 lb/acre N. Additionally, the final application of N should occur at bulb initiation to maximize yield and flavor potential.

In chapter 4 we determined the Nitrogen Fertilization Use Efficiency (FNUE) of N fertilizer applied at different developmental stages of short-day onions. The FNUE has never been evaluated for short-day onions cultivated in Georgia, but can provide key information for growers on how to manage fertilizer N applications throughout the season. We hypothesized that N fertilizer contributions to plant biomass accumulation would be minimal at early stages of growth, but as the season progresses and the bulbs begin to develop, the plant N requirement would increase, leading to higher FNUE. Our results showed that N fertilizer application at transplant was inefficient, with limited uptake by the plant. In contrast, application of N during bulb initiation and bulb swelling had the highest FNUEs.

Vidalia onions are also the most popular wholesale organic vegetable grown in Georgia. Because of this there is a significant need for information regarding organic fertilization strategies for onions grown in Georgia. In chapter 5 we compared two commercial organic fertilizers, a mixed source organic fertilizer (MIX) containing feather, blood, and bone meal and a pelleted poultry litter (PPL) applied at five rates and in two different soil types (Cecil sandy clay loam and Tifton loamy sand). We hypothesized that the MIX fertilizer would lead to higher yields at lower application rates compared to the PPL fertilizer, due to increased predicted mineralization rates of the MIX product. We found that increasing the rate of application of both organic fertilizers increased total yields of onion, but as expected, Nitrogen Uptake Efficiency (NUPE) decreased with increasing application rate. Onions in the Watkinsville, GA location (Cecil soil) had higher aboveground N accumulation than those in Tifton (Tifton soil), and the

MIX fertilizer outperformed the PPL fertilizer in terms of N accumulation and yield. No significant effects of fertilizer treatments were observed in onions grown in Tifton. These results suggest that the MIX fertilizer may be more effective for organic onion production in certain seasons, while the NUPE of PPL suggests its inefficiency, especially at high application rates.

Based on differences observed in our organic fertilizer study (Chapter 5) we developed a fourth study (Chapter 6) to determine the impact of temperature on N mineralization for three commonly used organic fertilizers in different soil types found in Georgia. The fertilizers were a MIX, PPL and feather meal (FM). Both the MIX and PPL fertilizers were used in the field study described in chapter 5. We hypothesized that N mineralization among various commercial organic fertilizers would be influenced by their distinct material compositions, and that temperature would impact the potential mineralizable N from organic fertilizers at different soils. We expected that higher temperatures would lead to an increase in N mineralization. The results indicated that predicting N mineralization from organic fertilizers was affected most by the fertilizer source and less so by soil type and temperature. Models effectively predicted N mineralization for FM and MIX fertilizers but were less accurate for predicting N release from PPL. After 120 days, FM exhibited the highest net N mineralization (Net N_{min}) (between 42% and 72% of total N applied), followed by MIX fertilizer (between 26% and 59%), while PPL had the lowest (between 0% and 22%). Overall, we determined that the source of organic fertilizer can substantially impact N availability during the growing season, and that among the soils tested, temperature and soil type may have a more limited influence on N mineralization.

In summary, the N fertilizer recommendations for conventional short-day onions in Georgia may be reduced without impacts on yield, but growers must be ready to adapt N rates depending on precipitation. Additionally, precise timing of N fertilizer application is key to maximize the FNUE and reduce N fertilizer inputs while maintaining bulb yield and quality. Organic onion growers should choose their organic fertilizer carefully for optimal N availability throughout the season, MIX and FM as providing more available N during the season compared to commonly used PPL fertilizers in Georgia.