Nitrogen

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Estimating Fertilizer Nitrogen-Use Efficiency in Transplanted Short-Day Onion

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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·ha^{-1} N, at one of five application times corresponding to a stage of development. All onions received a season total of 112 kg·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 8.9%, increasing to 26.4% 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 25.2%. This increased to 75.7% and 103% at 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.

Keywords: ^{15}N; N uptake; N harvest index; onion development stage

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1. 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.) [1]. Most active roots in onion are found in the upper 15 cm soil depth, while the maximum rooting depth is typically 30 cm [2–4]. In addition to being shallow-rooted, roots typically are limited to a radius of between 15–20 cm around each plant [5]. 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 in the Coastal Plain in southeastern Georgia, USA, where short-day onions are extensively cultivated. In these soils, N is vulnerable to leaching [6], making N fertilizer management a continual challenge for onion growers [7].

High rates of N fertilizers are usually applied to onion in the U.S. to increase the overall yields and bulb size [7–9]. Commercially acceptable yields have been achieved in Georgia, USA through the application of 117 kg·ha^{-1} N [10]. While high yields of onions are dependent on soil N availability, excessive N fertilizer application can have negative consequences such as N leaching, increased production cost and reduced bulb quality [11–13]. 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 [14,15]. 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 [7,9,10]. To maximize benefits from splitting N fertilizer applications, the timing of application should be synchronized with plant N demands at different stages of growth [10]. 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 [16].

Currently, little information is available on the FNUE of short-day onions in humid subtropical climates such as the one found in Georgia, USA [12,17]. The objective of this study was to evaluate the FNUE of short-day onions across five distinct developmental stages to optimize timing of fertilizer applications.

2. Materials and Methods

Field experiments were conducted during the 2021 and 2022 onion production seasons at the University of Georgia's Vidalia Onion and Vegetable Research Center, located in Lyons, GA, USA (32°00′58″ N, 82°13′17″ W). The region is classified as a humid subtropical climate and its soil is characterized as an Irvington loamy sand with 2% slope [18]. 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 was cut to a length of approximately 10 cm. Bareroot seedlings were then transplanted to the field on 10 December 2020 and 7 December 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 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 (Table 2). In each plot, the area adjacent to the ^{15}N subplots received unlabeled N in all application timings.

Table 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 was 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.

Table 2. Time of labeled-nitrogen (^{15}N) application and harvest in 2021 and 2022 in days after transplant (DAT).

Year	^{15}NT [1]	^{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 was 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 [19]. 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 [20].

Onions were harvested on 20 April 2021 (131 DAT) and 19 April 2022 (133 DAT) (Table 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 were 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 [21].

2.1. 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 [22]. 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 [23], using the following equations:

$$\text{Ndff} = \frac{\%\ ^{15}\text{N atom excess of the plant sample}}{\%\ ^{15}\text{N atom excess of the fertilizer applied}} \times \text{plant N uptake}\left(\text{kg}\cdot\text{ha}^{-1}\right) \quad (1)$$

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.

$$\text{FNUE} = \frac{\text{Ndff}}{\text{applied N rate}\left(\text{kg}\cdot\text{ha}^{-1}\right)} \times 100 \quad (2)$$

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

$$\text{NHI} = \frac{\text{kg}\cdot\text{ha}^{-1}\text{ of N in bulbs}}{\text{kg}\cdot\text{ha}^{-1}\text{ of N in whole plant}} \quad (3)$$

2.2. Statistical Analysis

Data were analyzed using the Linear Mixed Model from JMP Pro 16.0 (SAS Institute Inc., Cary, NC, USA). 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 ($\alpha = 0.05$).

3. Results

During the studies, there were 531 and 426 mm of rainfall in 2020 and 2021, respectively (Figure 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 [24].

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 constituted 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 (7487 kg·ha^{-1}) compared to 2022 (2079 kg·ha^{-1}). Nitrogen harvest index was greater in 2022 (0.81) compared to 2021 (0.54) (Table 3).

Table 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	7487 a	2.69 b	0.54 a
2022	58,404 a	10,272 a	46,053 a	2079 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). 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.

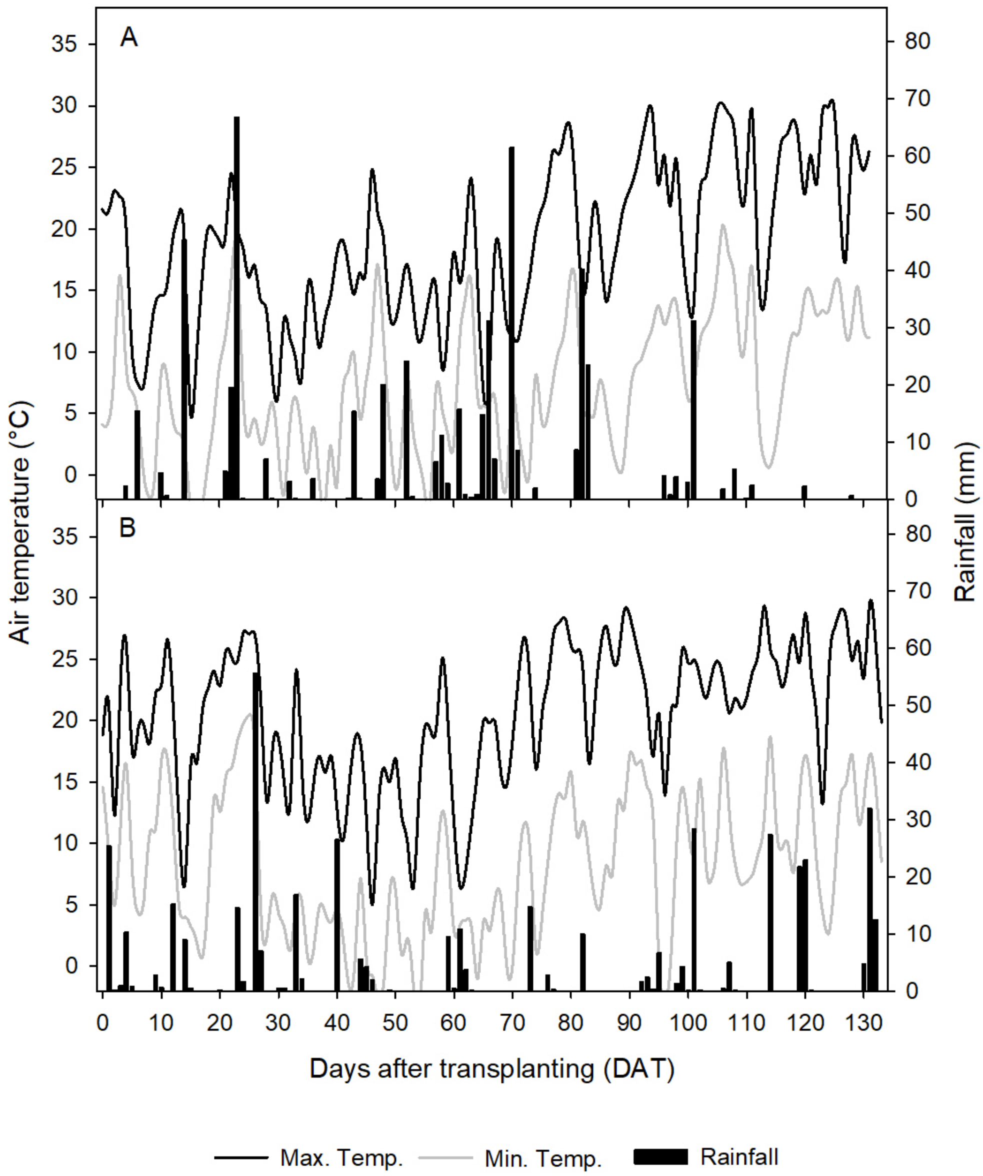

Figure 1. Daily maximum (max.) and minimum (min.) air temperatures (°C) and rainfall (mm) for onion (*Allium cepa* L.) grown during 2021 (**A**) and 2022 (**B**) in Georgia, USA. Data averages estimated using the University of Georgia Weather Network.

Table 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

Table 4. *Cont.*

Treatment	Bulbs	Leaves	Roots	Total Plant	FNUE (%)
	Ndff (kg·ha^{-1} ^{15}N)				
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 5).

Table 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 values at transplant, vegetative growth and bulb initiation were 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 up 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%). The FNUE values at bulb swelling and bulb maturation in 2022 were 77.6% and 53.3%, respectively.

4. Discussion

Recommended N application rates for onion production in the Coastal Plain region in Georgia, USA, range between 125 and 150 kg·ha^{-1} N [25]. However, da Silva et al. [10] reported that applying 117 kg·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·ha^{-1} N, split into five applications, throughout the onion-growing season and achieved commercially acceptable yields [25]. 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 1, Table 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, the 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 frequent rainfall during the production season.

Nitrogen uptake follows a sigmoidal curve in onion [16]. 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 [16]. Growers in Georgia, USA typically make their first N applications at or immediately after transplant to ensure fertilizer is available at plant establishment. 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).

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 [26]. Even if abundant N is available in the soil solution, plants may limit N uptake to maintain cytosolic pH balance and cellular homeostasis [26]. Foliar N concentrations peak early in onion development at values approaching 4% on a dry weight basis and then decline as aboveground biomass increases [27]. This is due to the relative decline in leaf area relative to overall biomass of plants and is termed the critical N dilution curve [28]. While overall total N content in the plant increases during growth as crop biomass increases, the relative concentration of N 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 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 [6] and rainfall that occurred within 30 DAT (Figure 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 an 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 biomass, which would increase total N accumulation, leading to a larger FNUE [26–28]. 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 [16]. 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 [6].

Nitrogen concentrations in leaf tissue above values which are necessary to maximize yield are often termed luxury consumption. In onion, luxury consumption of N is generally low [11]. 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 [1]. 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 [16]. 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 [16]. A relative increase in bulb size in 2022 (Table 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, flavor and storage quality compared to applications at bulb initiation or bulb swelling [14,29,30]. 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 [16,31]. 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 suggest 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 [16]. Interestingly, a season total N application of 112 kg·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·ha^{-1} N in an evaluation comparing different sources and rates of N fertilizers [31]. 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.

5. 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 was 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.

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