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Fertilizer Nitrogen Application for Short-Day Onion Production: From Field to Table

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Abstract: Long growing seasons, relatively shallow root system, coarse textured soils, and variability of the subtropical environmental conditions of the southeastern U.S. create challenges for nitrogen (N) fertilizer management of short-day onions. The objectives of this study were: (i) to evaluate the impact of fertilizer N rates on the yield and bulb quality of three short-day onion cultivars grown under the subtropical conditions of the southeastern U.S., and (ii) to assess the impact of fertilizer N rate for short-day onions on consumers' preference. Field experiments were conducted in 2019 and 2020 at the Vidalia Onion and Vegetable Research Center at the University of Georgia located in Lyons, GA, in which a two factorial experimental design of five fertilizer N rates (84, 101, 117, 134, and 151 kg of N ha^{-1}) and three short-day onion cultivars (Sweet Agent, Vidora, and Quick Start) was evaluated in a randomized complete block design. During both growing seasons, rainfall events directly impacted soil mineral N content. While soil mineral N availability increased with fertilizer N application, there was no significant difference among fertilizer N rate treatments due to rainfall distribution in both years studied, except at bulb initiation when the application of 117 kg of N ha^{-1} sustained soil mineral N availability that maximized with the application of 128 kg of N ha^{-1}. Onion total yield averaged 37,365 kg ha^{-1} in 2019 and 34,699 kg ha^{-1} in 2020. In general, colossal, jumbo, and medium-sized onions represented 7%, 76%, and 17% of total yield, respectively. Jumbo-sized onions are of most interest to growers due to their high value, and the yield of jumbo-sized onions was maximized with 158 kg of N ha^{-1} in 2019 and with 138 kg of N ha^{-1} in 2020. Bulb bacterial rots were not impacted by fertilizer N rate treatments. Contrarily, bulb gallic acid (GAE) linearly increased and pyruvic acid quadratically increased with the application of fertilizer N rate. Ultimately, a taste panel indicated that sensory characteristics were also not affected by different rates. Overall, a fertilizer N rate application of 117 to 134 kg of N ha^{-1} could sustain soil mineral N availability without impacting yield; however, an investigation on the timing of application should be conducted to determine a fertilizer N strategy that will promote optimum yield, bulb quality, flavor, and consumer acceptability.

Keywords: soil mineral nitrogen; onion yield; bulb quality; consumer preference

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1. Introduction

Onion (*Allium cepa*) is ranked as the fourth most valued vegetable crop in the U.S., grown in 21,748 ha and valued at more than $877 million [1]. Yellow onions are the most popular onion grown and comprise 87% of the national production area [2]. Yellow granex onions are a short-day onion type grown in the southeastern U.S., particularly in Georgia, where yellow granex onions are marketed as Vidalia onions, representing more than 4600 ha of production [3]. Vidalia onions are exclusively grown in the southeastern portion of Georgia, where mild winters, low sulfur soils, and sufficient water supply enhance the sweetness of short-day onions [4].

Short-day onions are characterized by relatively long growing seasons and shallow root system [4–6], which combined with the coarse textured soils and rainy spring seasons of the subtropical climate of southeastern U.S., create challenges for growers to maintain adequate soil nitrogen (N) availability during crop development [4]. Proper N fertilizer management is important to ensure profitable yields. Research on fertilizer N application for short-day onions in the southeastern U.S. began in the 1980s, when Batal et al. [7] reported no significant differences in yields among the application of 84, 168, and 224 kg N ha^{-1}. Later, Boyhan et al. [8] reported short-day onion yields were maximized with split fertilizer applications for a total N rate of 250 kg ha^{-1}. Currently, growers routinely produce high-yielding onion crops using lower N rates than those reported in the literature and less than the current fertilizer N recommendation of 125 to 150 kg N ha^{-1} [9] for the southeastern U.S.

Fertilizer N rates also influence the quality of short-day onions because of their impact on soil N availability. While a lack of soil N availability reduces onion yield, excess soil N may increase pungency (i.e., gallic acid and pyruvic acid concentrations) and reduce onion sweetness [10–12]. Ultimately, the N fertilization can impact bulb N concentrations [11,13], which can affect onion flavor and consumer acceptance [14].

Field-based research on the impact of N fertilization on onion yield and quality is limited. Further, there is no research showing the impact of N fertilizer on consumer preferences in short day onions. Thus, the objectives of this study are (i) to evaluate the impact of fertilizer N rates on the yield and bulb quality of three short-day onion cultivars grown under the subtropical conditions of the southeastern U.S., and (ii) to assess the impact of fertilizer N rate for short-day onions on consumers' preference.

2. Materials and Methods

Field experiments were conducted in 2019 and 2020 at the Vidalia Onion and Vegetable Research Center from the University of Georgia located in Lyons, GA (32°00′58″ N, 82°13′17″ W). The region is classified with a humid subtropical climate [15] and soil characterized as loamy sand texture with 0.6% of organic matter, 2% slope, and low water holding capacity [16].

2.1. Experimental Design and Crop Management

A two-factorial experimental arrangement with three short-day onion cultivars and five fertilizer N rates was evaluated in a randomized complete block design with four replications in both years. Short-day onion cultivars evaluated were Vidora, Quick Start, and Sweet Agent. Fertilizer N rate treatments consisted of the application of 84, 101, 117, 134, and 151 kg of N ha^{-1} applied as calcium nitrate ($15.5N - 0P_2O_5 - 0K_2O$) at 0, 30, 58, and 92 days after transplanting (DAT) in 2019, and at 0, 48, 70, and 96 DAT in 2020. Fertilizer application time followed growers' standard practices, and each application received 20% of the total N applied, except for the last application when 40% of the total N was applied.

Seeds of short-day onion cultivars were initially planted in nursery beds on 17 Septmber 2018 and 16 Septmber 2019, then transplanted to field beds on 19 December 2018 and 20 November 2019. Field beds were laid 15 cm tall and spaced at 1.82 m center to center, with each bed having four onion rows spaced approximately 25 cm apart, and onion seedlings were transplanted at an in-row spacing of 10 cm. A total of four adjacent field beds 113 m long were used, one per replication, in which experimental units were 7.0 m long with 1.5 m skip within each bed.

Short-day onions were overhead irrigated using stationary sprinklers. Irrigation water volume was determined according to the historical onion evapotranspiration. In addition to the N fertilizer application, short-day onions received a total of 120 and 180 kg ha^{-1} of phosphorus (P) and potassium (K) at 0 and 30 DAT using triple super phosphate ($0N - 45P_2O_5 - 0K_2O$) and muriate of potash ($0N - 0P_2O_5 - 60K_2O$), respectively. Crop management practices associated with insects, weeds, and disease management followed University of Georgia Extension recommendations.

2.2. Weather Conditions

An automated weather station from the Georgia Automated Environmental Monitoring Network (GAEMN—http://georgiaweather.net/, accessed on 15 February 2020) in Vidalia, GA, monitored rainfall and maximum and minimum air temperature during both growing seasons. Growing degr'ee days (GDD) were calculated by averaging the daily maximum and minimum air temperature minus the base temperature of 10 °C.

2.3. Soil Mineral N Availability

Soil samples collected five times during each growing season monitored the soil mineral N content. A soil sample comprised of five sub-samples in each plot was collected at 0–15 cm soil depth. Soil samples were collected before each fertilizer N application and at harvest. Soil samples were collected at 0, 30, 58, 92, 127 DAT in 2019 and at 0, 48, 70, 96, and 154 DAT in 2020. After being sampled, the soil of each sample was air dried, sieved, and tested for soil mineral N content (ammonium (NH_4^+) and nitrate (NO_3^-)) at a commercial laboratory (Waters Agricultural Laboratories, Camilla, GA, USA).

2.4. Short-Day Onion Harvesting and Bulb Quality

Short-day onions were harvested on 27 Apr. 2019 (127 DAT) and 14 Apr. 2020 (154 DAT). In both seasons, onion tops and roots were manually clipped, and bulbs were cured for a week with forced air at 38 °C, and graded into colossal (>9.5 cm), jumbo (8.25 to 9.5 cm), and medium (<8.25 cm) sizes, according to the United State Department of Agriculture standards for grades of Bermuda-Granex-Grano type onions. Total yield was calculated as the sum of colossal, jumbo, and medium bulbs. After harvest, onions were evaluated for sour skin (caused by *Pseudomonas cepacia*) and center rot (caused by *Pantoea* sp.), in which 20 jumbo-sized onions were cut in longitudinal orientation and the percentage of bulbs with center rot and sour skin damage was accessed.

Bulb total phenols expressed as gallic acid equivalents (GAE) and pungency measured as pyruvic acid were measured from a sample of 5 jumbo-sized onions. Total phenols were measured following the Folin–Ciocalteu Colorimetric method [17], in which 15 mL of extract and 1.185 mL of water was mixed with 0.07 mL Folin–Ciocalteu's reagent, followed by 0.225 mL 20% (*w*/*v*) sodium carbonate. After 30 min at 40 °C incubation, absorbance was measured at 756 nm, and total phenolic content was calculated as GAE. Onion pungency was measured using a 20 uL juice sample from which pyruvic acid was determined according to Lancaster and Boland [18].

2.5. Short-Day Onion Taste Panel

Two short-day onion taste panels were conducted after the 2019 harvest. The first panel was performed to compare onion cultivars (i.e., Vidora, Quick Start, and Sweet Agent), in which jumbo-sized onions of each cultivar grown under the fertilizer N rate of 135 kg ha^{-1} were tasted by 100 untrained panelists and ranked according to overall acceptability. Cultivar Sweet Agent was ranked as the most acceptable, followed by Vidora and Quick Start (data not shown). The second panel was conducted for comparison of fertilizer N rates, in which jumbo-sized onions of cultivar Sweet Agent, preferred by the first panel, were used. In this second panel, short-day onions grown under fertilizer N rates of 84, 100, 117, 135, and 151 kg of N ha^{-1} were sampled by 100 untrained panelists and scored for aroma, texture, sweetness, and overall acceptance. On the day of evaluation, panelists were presented with 25–30 g of diced onion from each fertilizer treatment in individual lidded polypropylene portions cups ("Conex Compliments model 200PC", Dart Container Corporation, Mason, MI, USA). Panelists were also provided with paper ballots for each sample (including a section on demographics) and a pencil as well as purified drinking water and unsalted top saltine crackers (Nabisco, East Hanover, NJ, USA) for palate cleansing. A balanced order of sample presentation was utilized, and all samples were performed under incandescent lighting. A nine-point hedonic scale (e.g., 9–like extremely, 8–like very much, 7–like moderately, 6–like slightly, 5–neither like nor dislike, 4–dislike slightly, 3–dislike moderately, 2–dislike very much, and 1–dislike extremely) was used to assess preference in each category. All human sensory research was conducted under the auspices of the University of Georgia Institutional Review Board, who approved consent documents and sensory ballots/techniques to ensure panelist safety and comply with guidelines on the ethical conduct of research.

2.6. Statistical Analysis

Data were analyzed using linear mixed techniques as implemented in SAS PROC GLIMMIX (SAS/STAT 14.2; SAS Institute Inc., Cary, NC, USA).

Total yield and yield of sized bulbs (i.e., jumbo, medium, and colossal) were analyzed with fertilizer N rate treatments (i.e., 84, 101, 117, 134, and 151 kg ha^{-1}), onion cultivar (i.e., Vidora, Quick Start, Sweet Agent), year (i.e., 2019 and 2020), and their interactions as main factors. Soil mineral N content was analyzed with fertilizer N rate treatments, onion cultivar, year, and sampling time (i.e., DAT for both seasons) as the main factors. In both analyses, block was treated as a random effect. When the *F* value was significant, multiple mean comparisons were performed using the Tukey test at a *p*-value of <0.05.

Taste panel results (i.e., scores for aroma, texture, sweetness, and overall acceptance) were analyzed with fertilizer N rate treatments (i.e., 84, 101, 117, 134, and 151 kg N ha^{-1}) as the main factor. All data were treated as categorical, and data distribution was analyzed as multinomial, which described the probability of a particular score to occur within the sampled population (100 panelists).

3. Results

3.1. Weather Conditions

Rainfall events accumulated 525 and 821 mm in 2019 and 2020, respectively (Figure 1). In 2019, rainfall events were evenly distributed during the entire season, with 194, 82, 83, and 164 mm of precipitation from onion transplanting to the vegetative stage, vegetative stage to bulb initiation, bulb initiation to bulb development, and bulb development to maturation, respectively. Rainfall events in 2020 were similar to 2019 in the early season; however, few isolated heavy rainfall events after bulb initiation increased rainfall accumulation in 2020. In 2020, 191, 75, 212, and 342 mm of rainfall occurred from onion transplanting to the vegetative stage, vegetative stage to bulb initiation, bulb initiation to bulb development, and bulb development to maturation, respectively.

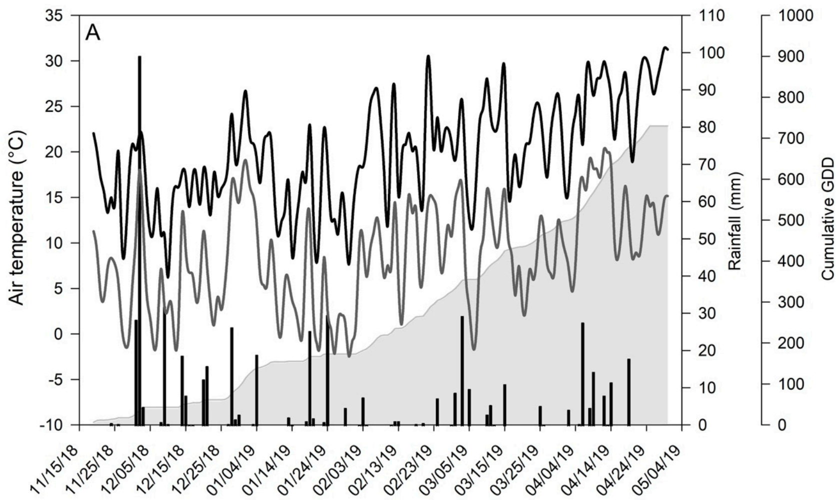

Figure 1. *Cont.*

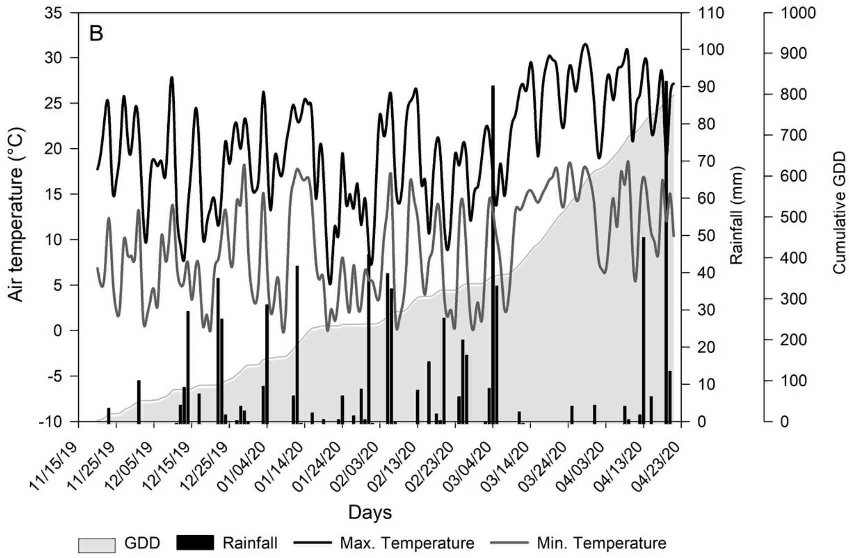

Figure 1. Weather conditions for the 2019 (**A**) and 2020 (**B**) short-day onion growing seasons, including maximum and minimum air temperature (°C), cumulative growing degree days (GDD), and rainfall events (mm). Data were recorded at 1-hr intervals and average retrieved from the Georgia Automated Environmental Monitoring Network at Vidalia, GA.

Average minimum and maximum daily air temperatures were similar in both growing seasons, ranging from 7 to 20 °C, respectively (Figure 1). Onion harvests occurred at 730 GDD in 2019 and 740 GDD in 2020.

3.2. Soil Mineral Nitrogen Availability

Soil mineral N availability increased during crop development in both growing seasons which was already expected since fertilizer N rates were applied at transplanting, vegetative stage, bulb initiation, and bulb development. However, soil mineral N was not significantly impacted by the interaction among year, cultivar, fertilizer N rate, and sampling time. Soil mineral N was significantly affected by the interaction between sampling time and fertilizer N rate. There were significant differences in soil mineral N concentrations for fertilizer N rate treatments measured at bulb initiation, but not at other developmental stages (Figure 2). Soil mineral N at bulb initiation had a positive quadratic response to fertilizer N rate, maximizing with the application of 128 kg of N ha^{-1}.

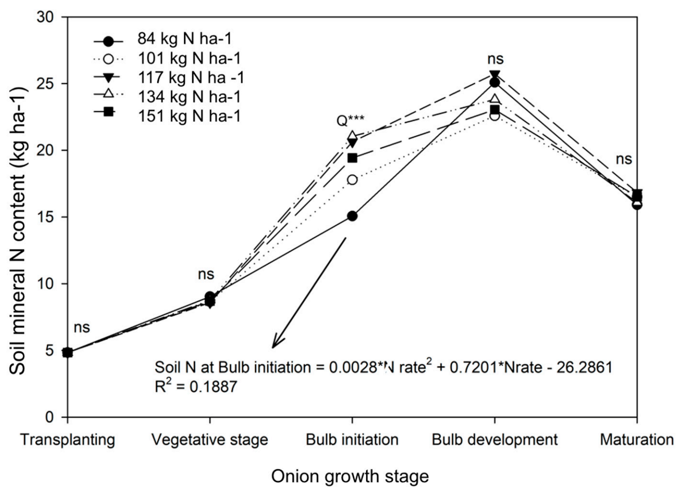

Figure 2. Effect of fertilizer nitrogen (N) rate application on the soil mineral N content at transplanting, vegetative, bulb initiation, bulb development, and maturation growth stages of short-day onions development. ns, non-significant; *** $p \leq 0.001$. Q means quadratic regression.

3.3. Onion Yield and Bulb Size Distribution

Short-day onions' total yield was not impacted by any interaction among year, cultivar, and fertilizer N rate; however, there were significant main effects of year and fertilizer N rate on total yield (Table 1). In general, total yield was significantly higher in 2019 (37,365 kg ha^{-1}) compared to 2020 (34,699 kg ha^{-1}) and had a significant quadratic and positive response to fertilizer N rate, in which total yield maximized with the application of 156 kg of N ha^{-1} (Figure 3).

Table 1. Effect of year, cultivar, fertilizer nitrogen (N) rate, and their interaction on total yield and yield of medium, jumbo, and colossal onion sizes.

Effect		Total		Medium		Jumbo		Colossal	
				kg ha^{-1}					
Year									
	2019	37,365 ± 4677 [‡]	a [†]	9405 ± 3325	a	27,723 ± 6550		660 ± 129	b
	2020	34,699 ± 5799	b	2880 ± 1365	b	27,353 ± 3657		4109 ± 1677	a
	p-value	***		***		ns		***	
Cultivar									
	Vidora	37,214 ± 5098		6452 ± 3939	ab	28,737 ± 5291	a	2025 ± 1070	
	Sweet Agent	35,247 ± 5412		4954 ± 2393	b	27,824 ± 5232	a	2469 ± 1346	
	Quick Start	35,730 ± 5530		7021 ± 4447	a	26,051 ± 5674	b	2658 ± 1444	
	p-value	ns		***		*		ns	
Fertilizer N rate (kg of N ha^{-1})									
	84	29,123 ± 3309		8307 ± 4840		20,287 ± 4334		529 ± 156	
	101	33,607 ± 3460		6608 ± 3779		25,438 ± 3118		1561 ± 1007	
	117	37,166 ± 3068		6136 ± 4429		28,710 ± 2100		2320 ± 1277	
	134	37,539 ± 4360		5020 ± 3376		30,527 ± 2636		1992 ± 1039	
	151	40,265 ± 5785		4573 ± 3090		31,638 ± 4026		4054 ± 1699	
	p-value	Q ***		L ***		Q ***		L ***	
Year*Cultivar		ns		ns		ns		ns	
Year*Fertilizer N rate		ns		2019 L *** 2020 L ***		2019 Q *** 2020 Q ***		ns	
Cultivar*Fertilizer N rate		ns		ns		ns		ns	
Year*Cultivar*Fertilizer N rate		ns		ns		ns		ns	

ns, Non-significant; * $p \leq 0.1$ and *** $p \leq 0.001$. Linear (L) or quadratic (Q) regression. [‡] Means the standard deviation. [†] Within a column, values within effects followed by the same lowercase letter indicate no significant difference between treatments according to the Tukey adjustment.

Year and fertilizer N rate significantly interacted to affect the yield of medium-sized onion bulbs. Yield of medium bulbs was also significantly impacted by the main effect of onion cultivar (Table 1). The yield of medium-sized onions was higher in 2019 (9405 kg ha^{-1}) than in 2020 (2880 kg ha^{-1}) and had a negative linear response to fertilizer N rate applications in both years (Figure 3). Vidora (6452 kg ha^{-1}) and Quick Start (7021 kg ha^{-1}) had a higher yield of medium-sized onions than Sweet Agent (4954 kg ha^{-1}).

Year and fertilizer N rate interacted to affect the yield of jumbo-size onion bulbs. Additionally, the main effect of cultivar significantly affected yield of jumbo bulbs (Table 1). Yields of jumbo bulbs in 2019 (27,723 kg ha^{-1}) and 2020 (27,353 kg ha^{-1}) were similar and had a positive quadratic response to N rate application in both years (Figure 3). The yield of jumbo bulbs was maximized with the application of 158 kg of N ha^{-1} in 2019 and 138 kg of N ha^{-1} in 2020. For the main effect of cultivar, Vidora (28,737 kg ha^{-1}) and Sweet Agent (27,824 kg ha^{-1}) had higher yields of jumbo-sized onions than Quick Start (26,051 kg ha^{-1}).

The yield of colossal-sized onions was not impacted by any interaction among year, cultivar, and fertilizer N rate; however, it was significantly affected by the main effect of year and fertilizer N rate (Table 1). The yield of colossal-sized onions was lower in 2019 (660 kg ha^{-1}) compared to 2020 (4109 kg ha^{-1}), and significantly increased with the increase of the fertilizer N rate (Figure 3D).

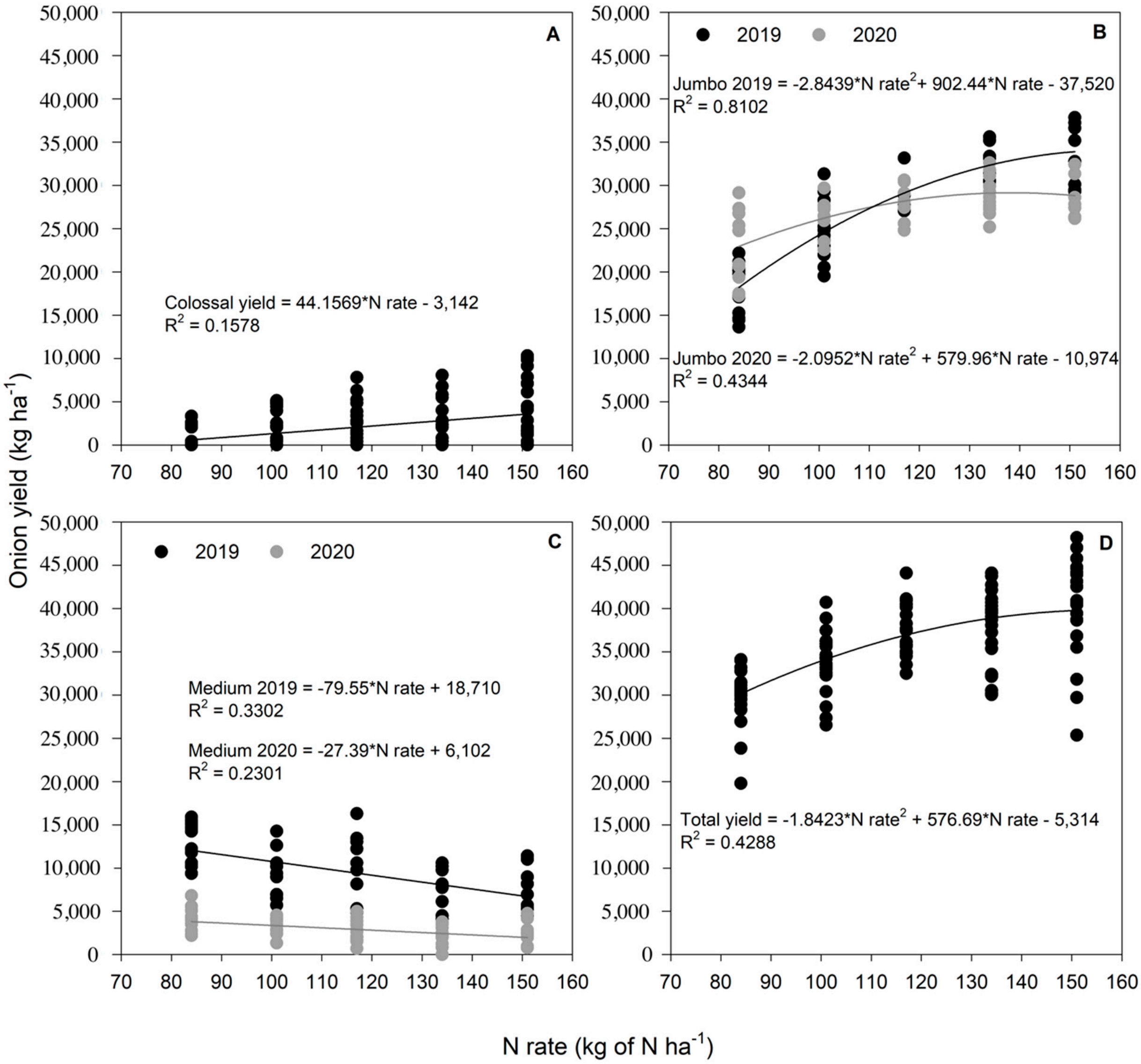

Figure 3. Response of short-day onion yield of colossal (**A**), jumbo (**B**), and medium (**C**) sizes and total yield (**D**) to fertilizer nitrogen (N) rates for the growing seasons of 2019 and 2020. Note = * means multiplication sign.

3.4. Bulb Quality

Onion sour skin incidence was impacted by the interaction between year and cultivar (Table 2). In 2019, sour skin incidence was higher for cultivar Vidora (19%) and Sweet Agent (11.4%) compared to Quick Start (8%). There were no symptoms of sour skin in 2020, regardless of cultivar (Table 3). Onion center rot incidence was affected by an interaction between year and cultivar (Table 2). In 2019, rates of center rot were higher for cultivar Sweet Agent (7.8%) compared to Vidora (0.5%) and Quick Start (1%). In 2020, center rot was not present in any cultivar (Table 3). In general, fertilizer N rate treatments had no impact on onion sour skin and center rot.

There was no interaction among year, cultivar, and fertilizer N on bulb GAE; however, there was a significant main effect of year and fertilizer N rate on onion GAE (Table 2). In this case, GAE was lower in 2019 (128.6 mg L^{-1}) compared to 2020 (259.2 mg L^{-1}), while GAE had a significant linear increase in response to fertilizer N rate (GAE = 0.3911*N rate + 145.55).

Table 2. Effect of year, cultivar, fertilizer nitrogen (N) rate, and their interaction on onion sour skin, center rot, gallic acid equivalent (GAE), and pyruvic acid.

Effect		Sour Skin		Center Rot		GAE		Pyruvic Acid	
		%		%		mg L^{-1}		Mn	
Year									
	2019	12.8 ± 12.3 ‡	a †	3.1 ± 8.9	a	128.6 ± 19.8	b	4.73 ± 1.08 a	
	2020	0.0 ± 0.0	b	0.0 ± 0.0	b	259.2 ± 40.1	a	4.46 ± 1.43 b	
	p-value	***		**		***		**	
Cultivar									
	Vidora	9.5 ± 12.1	a	0.3 ± 0.0	b	188.9 ± 68.1		5.24 ± 1.26	a
	Sweet Agent	5.7 ± 11.3	b	3.9 ± 10.4	a	195.2 ± 69.7		4.15 ± 1.05	b
	Quick Start	4.0 ± 8.1	b	0.5 ± 3.1	b	197.6 ± 81.5		4.39 ± 1.25	b
	p-value	***		***		ns		***	
Fertilizer N rate (kg of N ha^{-1})									
	84	5.0 ± 8.0		0.0 ± 0.0		176.9 ± 70.1		3.70 ± 1.57	
	101	6.7 ± 10.0		2.3 ± 6.7		190.3 ± 74.2		4.83 ± 0.90	
	117	5.0 ± 9.8		0.4 ± 2.0		194.1 ± 82.0		4.98 ± 1.21	
	134	6.8 ± 10.5		2.6 ± 8.8		198.7 ± 66.9		4.79 ± 1.24	
	151	8.5 ± 13.9		2.5 ± 8.9		209.5 ± 74.9		4.68 ± 1.24	
	p-value	ns		ns		L *		Q *	
Year*Cultivar		***		***		ns		**	
Year*Fertilizer N rate		ns		ns		ns		ns	
Cultivar*Fertilizer N rate		ns		ns		ns		ns	
Year*Cultivar*Fertilizer N rate		ns		ns		ns		ns	

ns, Non-significant; * $p \leq 0.1$; ** $p \leq 0.01$; and *** $p \leq 0.001$. Linear (L) or quadratic (Q) regression. ‡ Means the standard deviation. † Within a column, values within effects followed by the same lowercase letter indicate no significant difference between treatments according to the Tukey adjustment.

Table 3. Effect of the interaction between cultivar and year on onion sour skin, center rot, and pyruvic acid.

Cultivar	Year 2019			Year 2020		
			Sour skin (%)			
Sweet Agent	11.4 ± 13.8 ‡	a †	A	0.00 ± 0.0	a	B
Quick Start	8.0 ± 10.0	b	A	0.00 ± 0.0	a	B
Vidora	19.0 ± 10.7	a	A	0.00 ± 0.0	a	B
			Center rot (%)			
Sweet Agent	7.80 ± 13.6	a	A	0.00 ± 0.0	a	B
Quick Start	1.00 ± 4.4	b	A	0.00 ± 0.0	a	B
Vidora	0.50 ± 0.0	b	A	0.00 ± 0.0	a	B
			Pyruvic acid (Mn)			
Sweet Agent	3.85 ± 1.03	b	A	4.44 ± 0.99	ab	A
Quick Start	5.49 ± 0.58	a	A	5.00 ± 1.67	a	A
Vidora	4.85 ± 0.84	a	A	3.94 ± 1.45	b	B

‡ Means the standard deviation. † Within a column, values within effects followed by the same lowercase letter indicate no significant difference between treatments according to the Tukey adjustment.

Pungency was affected by an interaction between year and cultivar as well as the main effect of fertilizer N rate (Table 2). For the interaction between year and cultivar, year had a minimal impact on pyruvic acid and no significant differences were measured among years for cultivars Quick Start and Vidora. However, bulbs of cultivar Sweet Agent had higher pyruvic acid concentrations in 2019 than in 2020. In general, the pyruvic acid of cultivars Quick Start and Vidora were the highest in 2019, while Quick Start had the highest pyruvic acid in 2020. For the main effect of fertilizer N rate (Table 2), pyruvic acid quadratically responded to fertilizer N rate (Pyruvic acid = 0.0006*N rate^2 + 0.1618*N rate − 5.0071), which maximized with the application of 134 kg of N ha^{-1}.

3.5. Short-Day Onions Consumer Acceptability

Fertilizer N rate did not impact consumer opinions (Figure 4). Overall, panelists tended to neither like nor dislike the aroma (mean = 5.60) or sweetness (mean = 5.98) of short-day onions. Consumer panelists slightly like the texture (mean 6.66) and scored overall acceptance as slightly acceptable (mean = 6.01).

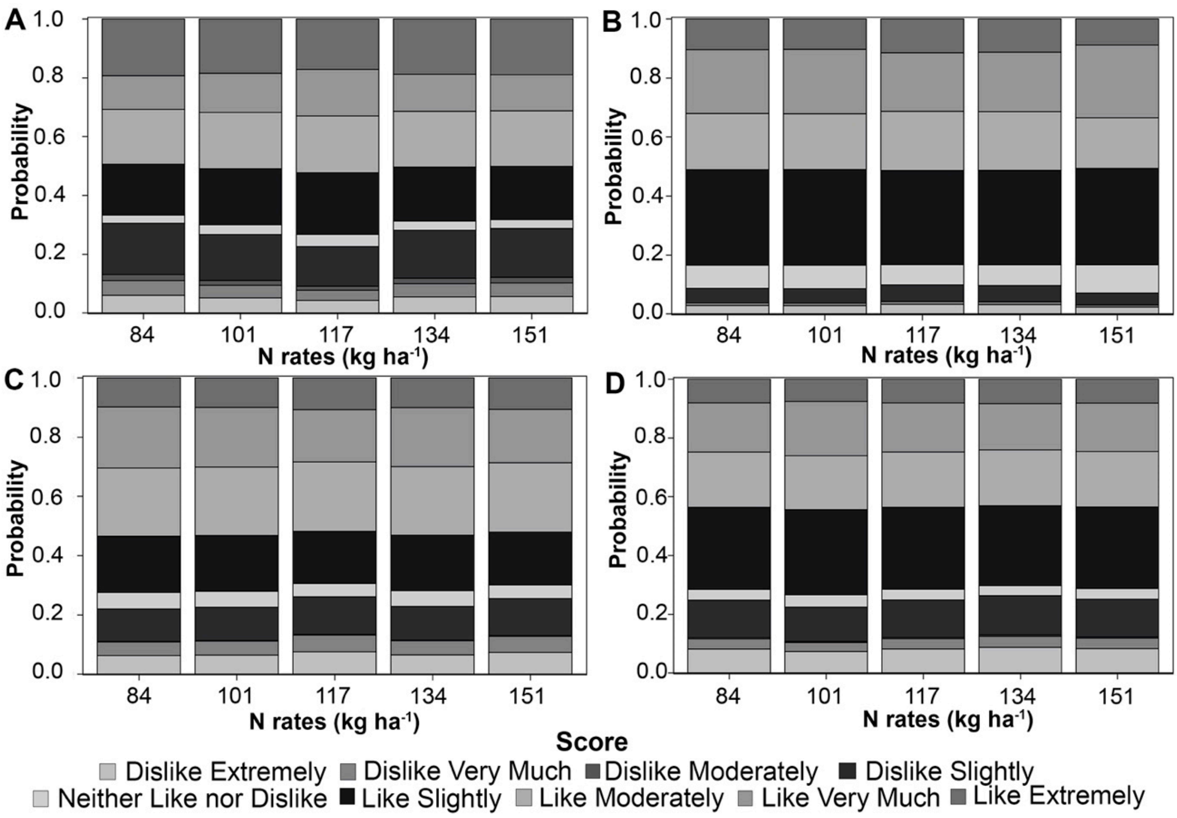

Figure 4. Probability distribution of a nine-point Hedonic score (i.e., 9–like extremely, 8–like very much, 7–like moderately, 6–like slightly, 5–neither like nor dislike, 4–dislike slightly, 3–dislike moderately, 2–dislike very much, and 1–dislike extremely) for aroma (**A**), texture (**B**), sweetness (**C**), and overall acceptance (**D**) of short-day onions grown under the fertilizer nitrogen (N) rates of 84, 101, 117, 134, and 151 kg N ha^{-1}.

4. Discussion

Weather conditions during the production season influence productivity and quality of short-day onions grown in the southeastern U.S. Daily air temperatures impact bulb development while rainfall events affect soil mineral N availability that can affect total yield, size distribution, and bulb quality [4].

Optimum daily air temperatures for short-day onion development are between 15 and 25 °C [19]. Air temperature patterns among the two years studied were similar and fell within the optimal ranges for short-day onion production. In general, daily air temperatures were lower early in the season and slowed onion growth, but daily air temperatures increased later in the season, accelerating GDD accumulation (Figure 1) and inducing onion growth and development. Whether the low air temperatures early in the season or high temperature late season were followed by heavy rainfall events or frequent rainfall events after fertilizer N application, soil mineral N availability reduced due to the soil mineral N leaching commonly reported in coarse textured soils [20], which resulted in the lack of significant differences in soil mineral N among fertilizer N rates early and late in the production season. In contrast, there were few mid-season rainfall events between the second and third fertilizer N application, resulting in a positive quadratic response of soil mineral N availability to fertilizer N rates at bulb initiation.

Soil mineral N responses to fertilizer N rate application in the present study were similar to those previously reported in cabbage [21,22], potato [23], bell pepper [24], and even onion [8,25] grown in coarse textured soils during the spring season of southeastern U.S. Results from the present study indicate that the fertilizer N rate of 117 kg of N ha^{-1} was adequate to sustain soil N availability. However, our results also suggest that growers may adjust fertilizer N application timing according to weather patterns and stages of growth development. For example, short-day onions have a shallow root system that is poorly distributed in the soil in the early season, and N applications at this stage should be minimal. As short-day onions enter the vegetative, bulb initiation, and bulb development stages of crop development, soil mineral N demands increase, and fertilizer N rates must correspondingly increase to maximize yield [6]. Still, rainfall events may lead to soil mineral N leaching, and fertilizer N rates should be applied accordingly to supply short-day onion requirements and maximize yield.

Colossal, jumbo, and medium-sized onions, on average, represented 7%, 76%, and 17% of total yield, and the distribution was similar to the distribution reported in the region by the Vidalia Onion Committee [26]. Growers are most interested in the jumbo-sized onions among all onion size distributions because of their higher value. Jumbo onions had a positive quadratic response to fertilizer N rates in both years, which was previously reported by Boyhan et al. [8] in trials conducted at the same research site. However, Boyhan et al. [8] noted that the yield of jumbo-sized onions was maximized with 283 kg of N ha^{-1}, while the present study reported that the yield of jumbo-sized onions was maximized with 158 kg of N ha^{-1} in 2019 and 138 kg of N ha^{-1} in 2020. The difference in fertilizer N rates required to achieve maximum yields of jumbo-sized onions between both years studied should be attributed to the different rainfall patterns [6]. Nevertheless, the lower fertilizer N rate required to achieve maximum yields in the present study is lower than those previously reported in the literature [8,20,27], highlighting the relative higher fertilizer N use efficiencies of new cultivars of short-day onion, in which optimum fertilizer N rate application would vary between 117 and 134 kg of N ha^{-1}. This suggests that future studies may focus on fertilizer application timing [6] rather than evaluating fertilizer N rates above the recommendation of 168 kg of N ha^{-1} as suggested by Boyhan et al. [8].

Sour skin and center rot symptoms on short-day onions were present in 2019 but not in 2020. Sour skin and center rot were not affected by the fertilizer N rate treatments. This suggests that sour skin and center rot are more affected by soil moisture levels due to rainfall during bulb development (Figure 1) rather than soil mineral N availability (Figure 2). Similar results were reported by Ncayiyana et al. (2019), who reported no significant difference in center rot among fertilizer N applications of 0, 30, 60, 90, 120, or 180 kg of N ha^{-1}.

In the present study, fertilizer N rate positively impacted GAE concentrations. Gallic acid is one of the main phenolic compounds in yellow onions and is associated with the antioxidant capacity of onion bulbs [28]. This may contribute to the overall bulb quality and improved shelf life of stored onions [29]. Volatile compounds contribute to the aroma of onions, which can impact overall flavor perception by consumers. Sulfur-containing compounds constitute the major volatile compounds in fresh onions, including mono-, di-, and trisulfides [30]. Sulfoxide compounds are responsible for the flavor and aroma of onions [31]. Different fertilization regimes have previously been shown to influence the onion flavor profile [32]. As an example, Coolong and Randle [14] demonstrated that N availability directly influenced the levels of S-methyl-L-cysteine sulfoxide, a precursor of pyruvic acid in freshly cut short-day onions, which authors suggested might affect flavor quality in the bulb. In the present study, a positive linear interaction effect was measured on fertilizer N rates and pyruvic acid levels, but these differences appear to have been below the detectible threshold of our untrained panel, as there were no significant differences in either flavor, aroma, or overall acceptability.

5. Conclusions

Fertilizer N rates were evaluated with three short-day onion cultivars grown in two consecutive seasons under the subtropical environmental conditions of southeastern U.S. Air temperatures impacted the time to onion maturity, and rainfall affected soil mineral N content in both growing seasons. Soil mineral N was not affected by fertilizer N rates, except at bulb initiation, when soil mineral N availability had a quadratic response to fertilizer N rates. Particularly, soil mineral N content was maximized with the application of 128 kg of N ha^{-1} at bulb initiation. The yield of jumbo-size onions had a quadratic response to fertilizer N rate treatments and was maximized with the application of 158 and 138 kg of N ha^{-1} in 2019 and 2020, respectively. The yield of medium-size onions had a negative linear relationship with fertilizer N rate treatments, while the yield of colossal-size onions increased with the increasing fertilizer N rates. Bulb quality parameters, such as sour skin and center rot, were not impacted by fertilizer N rate treatments but were affected by year, which was likely due to the rainfall distribution during bulb development. Bulb quality parameters, such as GAE and pyruvic acid were significantly impacted by fertilizer N rate. GAE increased linearly with fertilizer N rate, while pyruvic acid quadratically increased with fertilizer N rate. Both GAE and pyruvic acid are associated with sensorial characteristics of onions (i.e., aroma, texture, sweetness, and overall acceptance), which were evaluated in a taste panel. Sensory characteristics were not affected by different fertilizer N rates. Our results suggest a fertilizer N rate application between 117 and 134 kg of N ha^{-1} may be considered optimum for short-day onions grown in southeastern U.S.; however, future studies may focus on the timing of fertilizer N rate application and effect on yield, bulb quality, flavor, and consumer acceptability.

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