Sweet Onion (*Allium cepa* L.) as Influenced by Organic Fertilization Rate: 1. Plant Growth, and Leaf and Bulb Mineral Composition

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Abstract. Vidalia onions (*Allium cepa* L.) are sweet, short-day, low pungency, yellow Granex-type bulbs that are popular in the United States because of their mild flavor. There are limited studies on sweet onion plant growth in response to organic fertilization rate. The objective of this report was to evaluate the effects of organic fertilizer rates on sweet onion plant growth, and leaf and bulb mineral nutrients. Experiments were carried out at the Horticulture Farm, Tifton Campus, University of Georgia, in the Winters of 2012–13 and 2013–14. There were five treatments [organic fertilizer 3–2–3 equivalent to 0, 60, 120, 180, and 240 kg·ha⁻¹ nitrogen (N)]. During the season and at the mature plant stage, root, stem, and bulb biomass increased whereas the root-to-shoot ratio decreased with increasing fertilization rate up to 120 kg·ha⁻¹ N. Foliar concentrations of N and Ca decreased whereas Cu concentration increased with increasing organic fertilization rate. Bulb Mg and Mn increased whereas P and Cu decreased with increasing organic fertilization rate. The accumulation of mineral nutrients by onion whole plants increased quadratically (N, P, K, and S) or linearly (Ca and Mg) with increasing fertilization rate. The N use efficiency decreased with increasing organic fertilization rate; the agronomic efficiency of N (AEN) decreased quadratically and the marginal yield decreased linearly with increasing fertilization rate. Chlorophyll indices (CI) were highest with 240 kg·ha⁻¹ N and lowest with 0 kg·ha⁻¹ N. In conclusion, onion plant growth increased with increasing organic fertilizer rate probably because of augmented soil N levels. Observation of nutrient deficiencies late in the season, even at high organic fertilization rates, indicates that preplant application of organic fertilizer was sufficient to cover plant nutritional needs only partially and that applications of N fertilizer later in the season may be necessary. High application rates of organic fertilizer (above those required by the crop) may have resulted in significant N leaching because it is unlikely that the crop used most of the N that was mineralized. Bulb concentrations of P, K, Ca, Mg, S, B, Fe, Cu, and Mn were higher compared with values reported in the literature for onions produced with inorganic fertilizers.

Vidalia onions (*Allium cepa* L.) are sweet, short-day, low pungency, yellow Granex-type bulbs that are popular in the United States because of their mild flavor (Boyhan and Torrance, 2002). Vidalia onions are exclusively grown in Southeastern Georgia, in a region that includes 20 counties, where there are mild winters and low-sulfur soils (<0.001 mg·L⁻¹). There is increased interest in the utilization of organic fertilizers because of the growing demand of organic vegetables including organic sweet onions. There is, however, limited information about application rates of organic fertilizers to vegetable crops.

Most fertilizer recommendations for vegetable crops were developed for crop production based on the use of chemical fertilizers. When chemical fertilizers are used, there is

precise and ready nutrient availability. By contrast, soil nutrient release and availability, particularly those of N, are complex and variable with organic fertilizers, which make current fertilizer recommendations often not applicable. In the past, the main goal of N management in agriculture was to maximize yields and economic return. Presently, N management should look for a balance between food production, profit, and environmental quality (Bock and Hergert, 1991). The most used practice to determine the amount of organic fertilizer to apply is to consider the N content of the organic fertilizer and the crop N needs (Davis et al., 2017).

The availability of N may differ depending on the source of organic fertilizer and environmental conditions. The N in organic

fertilizer may be partially in an inorganic form (nitrate or ammonia, readily available to plants) but N is primarily in an organic form (not readily available to plants). Nitrogen mineralization is the process by which soil microorganisms transform organic N in organic fertilizers into NH₄⁺-N. Nitrogen mineralization increases with temperature (Agehara and Warncke, 2005). Nitrogen mineralization consists of a sequence of enzymatic reactions for which the living microbial biomass provides the enzymes and the dead microbial biomass the substrate (Mengel, 1996).

Organic fertilizers vary in elemental nutrient concentrations and rates of nutrients release. In a lettuce (*Lactuca sativa* L.) pot study, of the total N applied (200–800 kg·ha⁻¹), available N over 6 months was 50% to 70% with feather meal and poultry manure compost treatments, 10% to 40% with alfalfa meal, and 10% with vermicastings. Application rates above 800 kg·ha⁻¹ did not result in corresponding increases in nutrient supply (Hammermeister et al., 2006).

Insufficient soil N availability is frequent in organic vegetable production because of unpredictable N release. Tomato plants grown in a substrate containing 20% to 40% compost (yard waste or yard waste plus swine manure) could not be sustained for more than 1 month before nutrient deficiencies became visible. However, when the compost rate was increased to 50%, organic yields were similar to those of tomatoes grown in a hydroponic system (Zhai et al., 2009).

Rates of N mineralization in seabird guano, hydrolyzed fish powder, feather meal, and blood meal ranged from 47% to 60% after 2 weeks and from 60% to 66% after 8 weeks; temperatures (10 or 25 °C) had minor effects on the rate of N mineralization (Hartz and Johnstone, 2006). In another study, a liquid organic fertilizer containing fishery wastes and seabird guano showed rapid nitrification, with >90% of mineral N in the nitrate form observed after 1 week of incubation at 25 °C, or 2 weeks at 15 °C (Hartz et al., 2010).

In addition to being a source of mineral elements to plants, organic fertilizers provide food for soil microbiota. Short-term application of horse manure and compost greatly stimulated soil microbial biomass C, N, and P, fungal ergosterol, and CO₂ evolution, but failed to stimulate productivity of field peas (*Pisum sativum* L.), either as a sole crop or intercropped with oat (*Avena sativa* L.) (Jannoura et al., 2013). In an onion study, top weight was lower with organic fertilizers compared with chemical fertilizers (Lee, 2010).

The objective of this study was to evaluate the effects of organic fertilization rates on sweet onion plant growth and mineral nutrients composition in leaves and bulbs. In a companion article (Díaz-Pérez et al., 2018) from the same trial as this study, we report on the effects of organic fertilization rate on bulb yield and quality.

Materials and Methods

Land preparation and planting. Experiments were conducted at the Horticulture Farm, Tifton Campus, University of Georgia, in the Winter of 2012–13 and 2013–14. The farm is located at an altitude of 108 m above mean sea level, lat. 31°28'N and long. 83°31'W. The soil of the experimental field is a Tifton sandy loam (a fine loamy, siliceous, thermic Plinthic Kandiudults) with an organic matter content of 0.5% and a pH of 6.5. In addition to onion, the field is used to grow solanaceous and cucurbit crops and cover crops, such as cereal rye (*Secale cereale*) and pigeon pea (*Cajanus cajan*); these crops are fertilized chemically. Because of the high rainfall and the low organic matter content of Georgia soils (as that of this study), there is very low residual N available for the crop (Kissel and Sonon, 2008). The concentration of macronutrients in the soil before planting in 2012 and 2013 were, respectively, P (39 and 35 mg·kg⁻¹), K (35 and 27 mg·kg⁻¹), Ca (511 and 523 mg·kg⁻¹), Mg (90 and 76 mg·kg⁻¹), and S (21 and 18 mg·kg⁻¹).

Plants were grown on raised beds (1.8 m from center to center of each bed). Each bed had four rows 23-cm apart, with an in-row plant spacing of 15 cm. Beds were covered with black plastic film mulch; there were two lines of drip tape per bed; each drip tape was located midway between alternate rows. The drip tape (Ro-Drip; Roberts Irrigation Products Inc., San Marcos, CA) had 10 cm emitter spacing, 0.50 L·h⁻¹ emitter flow at 5631 kg·m⁻² pressure, and 0.2 mm wall thickness, and was buried 3 cm deep. Plants were irrigated with ≈4 mm per week in one weekly application from transplanting to the period of rapid bulb enlargement (mid-March). From the period of rapid bulb enlargement to bulb harvest, plants were irrigated with ≈12 mm per week in one to two weekly applications. To minimize nitrate leaching, each irrigation was ended when soil water content was at approximately field capacity. Soil water content (volumetric) in the 0–12 cm of soil profile was measured with a portable time domain reflectometry (TDR) sensor (CS-620; Campbell Scientific, Logan, UT). The two metallic 12-cm rods of the TDR sensor

were inserted vertically within the row between two plants.

Before laying the plastic mulch and before transplanting, N was applied to the soil as organic fertilizer (microSTART60 3–2–3; Perdue AgriRecycle, LLC, Seaford, DE). The organic fertilizer was incorporated, only to

the bed area, with a rototiller-bed shaper. MicroSTART60 consists entirely of chicken litter, a by-product of the poultry industry. No additional fertilizer was applied after transplanting. Eight-week old onion seedlings 'Yellow Granex PRR' grown at the Vidalia Onion and Vegetable Research Center,

Fig. 1. Seasonal trends of maximal, mean, and minimal air temperature and rainfall. Tifton, GA, Winters of 2012–13 and 2013–14.

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University of Georgia, Lyons, GA, were transplanted on 12 Dec. 2012 and 2013.

Experimental design and treatments. The experimental design was a randomized complete block with six replications and five treatments (N rate). The experimental unit consisted of a 6.1-m long bed. The likelihood of treatment contamination between beds was low because of the distance between beds and because of the placement of the organic fertilizers under the plastic mulch, which minimized potential spillover effects. The applied organic fertilization rates were equivalent to 0, 60, 120, 180, and 240 kg·ha⁻¹ N.

Plant growth. Shoot, root, and bulb dry weight were measured weekly during the entire season until harvest time on two plants per plot. Plant samples were dried at 70 °C for several days until constant weight was obtained.

Harvest. Plants were harvested when 20% of the necks had collapsed (tops down) on 13 May 2013 and 12 May 2014. Onions were hand-harvested and roots and tops were clipped; bulbs were left in the field for 48-h curing.

Plant mineral nutrients. Immediately after harvest, 10 shoots per plot and three bulbs per plot were dried at 70 °C for 3 d, ground, and analyzed for mineral nutrient concentration at the University of Georgia Agricultural & Environmental Services Laboratories, Athens, GA. Mineral nutrient content was calculated by multiplying the plant part dry weight by its respective nutrient concentration. The accumulation of mineral nutrients by onion plants was computed as the summation of the mineral nutrient contents of the different plant parts (shoot, bulb, and root). Nutrient content per plant was expressed on a per-hectare basis based on a plant density of 143,458 plant/ha.

Nitrogen use efficiency was measured as AEN and as marginal yield (total bulb yield increase per added unit of N from the organic fertilizer). The AEN was calculated by dividing total onion fresh bulb weight (kg·ha⁻¹) by the amount of N (kg·ha⁻¹) applied to the crop (Bock and Hergert, 1991). Total onion bulb yield data are derived from the same plants of this study and are reported in a companion article (Díaz-Pérez et al., 2018).

Leaf chlorophyll index. Chlorophyll indices were determined weekly over the season on six well-exposed and healthy leaves per plot using a chlorophyll meter (Chlorophyll Meter SPAD-502; Minolta Co., Ltd., Ramsey, NJ).

Weather. Weather data (air temperature, reference evapotranspiration, and rainfall) were obtained from a nearby University of Georgia weather station (within 300 m).

Statistical analysis. Data were analyzed using the General Linear Model and Regression Procedures from SAS (SAS version 9.4; SAS Institute Inc., Cary, NC). The linear models chosen (linear or quadratic) were those with the highest *R*² and lowest *P* values. A segmented-linear regression model (SigmaPlot, version 13.0; Systat Software, Inc., San Jose, CA) was used for the Cu vs. N relationship (Fig. 4B) because linear

regression models were not appropriate for this relationship. Data from both years were pooled when no year × treatment interactions were found.

Results

Weather. Figure 1 shows the seasonal trends of maximal, mean, and minimum air temperature and rainfall in 2012–13 and 2013–14. In both seasons, temperatures were lowest for the first 60 d after transplanting

(DAT). In 2012–13, average maximum, mean, and minimum temperatures were 19.0, 13.6, and 8.2 °C, respectively, and cumulative rainfall was 807 mm. In 2013–14, average maximum, mean, and minimum temperatures were 18.6, 13.0, and 7.3 °C, respectively, and cumulative rainfall was 671 mm.

Shoot, root, and bulb growth. During the season (Fig. 2) and at the mature plant stage (Table 1), root and shoot dry weights increased whereas the root-to-shoot ratio decreased with increasing organic fertilization rate up to

Fig. 2. Mean seasonal growth of root (A), shoot (B), and bulb (C) and root-to-shoot ratio (D) in sweet onion plants as affected by organic fertilization rate. Tifton, GA, Winter of 2012–13. Two plants per plot were sampled weekly over the season. Nitrogen was provided by a commercial organic fertilizer [microSTART60 (3–2–3); Perdue AgriRecycle, LLC].

Table 1. Biomass of roots, bulbs, and shoots of mature sweet onion as influenced by organic fertilization rate. Two plants per plot sampled immediately after harvest. Nitrogen was provided by a commercial organic fertilizer [microSTART60 (3–2–3); Perdue AgriRecycle, LLC]. Tifton, GA, Winter of 2012–13.

Rate (kg·ha ⁻¹ N)	Dry wt (g/plant) ^a			Root-to-shoot ratio
	Root	Bulb	Shoot	
0	1.043	6.583	4.303	0.273
60	1.539	12.202	7.194	0.233
120	1.417	14.005	7.773	0.183
180	1.789	20.367	10.120	0.177
240	1.660	22.878	9.115	0.198
Significance ^b				
L	0.004	0.001	0.006	0.014
Q	0.083	0.005	0.011	0.010

^aTwo plants per plot sampled immediately after harvest.

^bL = linear; Q = quadratic response.

120 kg·ha⁻¹ N. There were no changes in root-to-shoot ratio with further increases in the organic fertilization rate. Bulb dry weight increased quadratically with increasing organic fertilization rate and no maximal bulb dry weight value was reached. Calculated as the first derivative from equations in Fig. 2A and B, optimal organic fertilization rates for biomass growth were 150 kg·ha⁻¹ N (root) and 193 kg·ha⁻¹ N (shoot). The bulb yield data are in a companion report (Díaz-Pérez et al., 2018). Briefly, sweet onion total and marketable yields and individual bulb fresh weight augmented quadratically with increasing organic fertilization rate and responses failed to reach a maximum.

Foliar and bulb mineral nutrients. In plants at the end of the growth cycle, foliar concentrations of N (Fig. 3A) and Ca (Fig. 3D) slightly decreased with increasing organic fertilization rate. The P concentration was lowest at intermediate organic fertilization rates (Fig. 3B). Foliar concentrations of K (Fig. 3C), Mg (Fig. 3E), and S (Fig. 3F) showed no significant response to organic fertilization rates. Among foliar micronutrients, Cu concentration increased with increasing organic fertilization rates up to 120 kg·ha⁻¹ N and then remained about constant with further increases in organic fertilization rates (Fig. 4B) whereas B (Fig. 4A), Fe (Fig. 4C), Mn (Fig. 4D), and Zn (Fig. 4E) concentrations were unaffected by organic fertilization rates.

With respect to bulb nutrients, P was reduced at rates above 120 kg·ha⁻¹ N; Mg and Mn increased whereas S ($P = 0.056$) and Cu decreased with increasing organic fertilization rates (Table 2). The other bulb nutrients were unaffected by organic fertilization rate. The accumulation of mineral nutrients by onion whole plants increased quadratically (N, P, K, and S) or linearly (Ca and Mg) with increasing organic fertilization rates (Fig. 5A–F).

Leaf CI. In both seasons, CI were highest with 240 kg·ha⁻¹ N and lowest with 0 kg·ha⁻¹ N (Fig. 6A and B). The differences in CI among treatments varied by dates. In 2013, in general, highest values of CI for all N rates were at approximately Julian days (JD) 40–50 and then decreased as the season progressed, except for treatment 0 kg·ha⁻¹ N which had reduced CI values that increased after approximately JD 90. In 2014, there were no differences in CI at JD 120 because of abrupt CI decline in treatments 180 and 240 kg·ha⁻¹ N.

The N use efficiency decreased with increasing organic fertilization rate. The AEN decreased quadratically with increasing fertilization rates from ≈ 311 to 144 kg·kg⁻¹ N (Fig. 7A). Marginal yield decreased linearly with increasing N rates (Fig. 7B).

Discussion

Shoot, root, and bulb growth. In mature plants of the present study (Table 1), root dry weight increased from 1.0 to 1.7 g/plant (increase of 70%), bulb dry weight increased

Fig. 3. Mean concentrations of leaf nitrogen (A), phosphorus (B), potassium (C), calcium (D), magnesium (E), and sulfur (F) in mature sweet onion plants as affected by organic fertilization rate. Tifton, GA, Winter of 2013 and 2014. Plants were sampled immediately after harvest. Nitrogen was provided by a commercial organic fertilizer [microSTART60 (3–2–3); Perdue AgriRecycle, LLC].

from 6.6 to 22.9 g/plant (increase of 247%), and shoot dry weight increased from 4.3 to 10.1 g/plant (increase of 135%) with increasing organic fertilization rate. The augmented onion plant growth observed with increasing organic fertilization rate was probably a result of the increased nutrient levels (N, primarily) in the soil. To achieve maximal growth, the calculated optimal organic fertilization rate required was lowest in roots (150 kg·ha⁻¹ N), followed by shoots (193 kg·ha⁻¹ N), and highest in bulbs (>240 kg·ha⁻¹ N). It was not possible to calculate the actual optimal organic fertilization rate for maximal bulb growth because the bulb dry weight vs.

organic fertilization rate response curve reached no maximal point (Fig. 2C), suggesting that even at the highest organic fertilization rate (240 kg·ha⁻¹ N), onion plants were deficient in N and possibly other nutrients.

In a study on the effects of K and S inorganic fertilization rates on sweet onion conducted on the same farm as the present study, simultaneously, and using the same cultivar and cultural practices, mean root, bulb, and shoot dry weights of mature plants (at harvest time) were 1.3, 23.1, and 12.7 g/plant, respectively (Díaz-Pérez et al., 2016). Results of the present study showed that compared with the onion plants of the K

Fig. 4. Mean concentrations of leaf boron (A), copper (B), iron (C), manganese (D), and zinc (E) in mature sweet onion plants as affected by organic fertilization rate. Tifton, GA, Winter of 2013 and 2014. Plants were sampled immediately after harvest. Nitrogen was provided by a commercial organic fertilizer [microSTART60 (3–2–3); Perdue AgriRecycle, LLC]. Sufficiency ranges for foliar micronutrients are 22–60 mg·kg⁻¹ B, 15–35 mg·kg⁻¹ Cu, 60–200 mg·kg⁻¹ Fe, 50–250 mg·kg⁻¹ Mn, and 25–100 mg·kg⁻¹ Zn (Bryson and Mills, 2014). $f = y_0 + a \times x$; $t_1 = \min(t)$; $t_2 = \max(t)$; $\text{region1}(t) = [y_1 \times (T_1 - t) + y_2 \times (t - t_1)] / (T_1 - t_1)$; $\text{region2}(t) = [y_2 \times (t_2 - t) + y_3 \times (t - T_1)] / (t_2 - T_1)$; $f = \text{if}[t \leq T_1, \text{region1}(t), \text{region2}(t)]$; $y_1 = 3.85$; $y_2 = 4.38$; $y_3 = 4.38$; $T_1 = 120$; $R^2 = 0.980$; $P = 0.179$.

and S study, root growth was enhanced by up to 31% in plants under organic fertilization (at rates ≥ 180 kg·ha⁻¹ N). Bulb dry weight at high organic fertilization rates of the present study was similar to bulb dry weight of the K and S study. In addition, shoot dry weight at high organic fertilization rate was $\approx 25\%$ smaller than shoot dry weight of the K and S study, suggesting that plants under organic fertilization, even at high organic fertilization rates, had access to less amount of available soil N compared

with plants in the K and S study. Possibly, preplant application of organic fertilizer resulted in a rapid N mineralization of the organic N in the first weeks after transplanting. During this period, however, there was low demand for N by the crop because plants were small and the rate of plant growth was reduced because of the low air and soil temperatures. Thus, much of this mineralized N was probably lost by leaching and, several weeks later, when plant demand for N was high (March–May), the available

soil N was likely insufficient to satisfy plants' nutritional needs.

In an incubation study, the rate of N mineralization from four organic fertilizers (seabird guano, hydrolyzed fish powder, feather meal, and blood meal) was rapid (Hartz and Johnstone, 2006). Within 2 weeks, N mineralization of organic N ranged between 47% and 60% and within 8 weeks, N mineralization ranged from 60% to 66%. Assuming that in the present study (21 weeks) only 65% of the organic N was mineralized, this would mean that in the highest organic fertilization rate (240 kg·ha⁻¹ N), ≈ 156 kg·ha⁻¹ N would be available as mineralized N. This amount of N would have been sufficient for the onion crop, considering that the recommended fertilization rate for sweet onions in Georgia is ≈ 150 kg·ha⁻¹ N applied as synthetic chemical fertilizer (Boyhan et al., 2007; Díaz-Pérez et al., 2003). Onion plants in the present study, however, at the highest organic fertilization rate showed reduced shoot growth and leaf chlorosis at the end of the season.

The root-to-shoot ratio of mature plants in the K and S study (mean = 0.100) was also reduced compared with the root-to-shoot ratio of mature plants (range from 0.273 to 0.198) of the present study. At low organic fertilization rates, onion plants of the present study showed increased root-to-shoot ratio because of increased root growth. As a survival strategy in nutrient-limiting conditions, to explore more soil volume, onion plants likely allocated more nutrients to the roots relative to the shoot and bulb. Water stress and N deficiency may increase the relative allocation of nutrients and assimilates to roots (Marschner, 2012). The increased root-to-shoot ratio, even at the highest organic fertilization rate of the present study, compared with the root-to-shoot ratio of plants in the K and S study further supports the proposal that plants under organic fertilization in the present study were under soil nutrient limiting conditions and that these conditions resulted in enhanced root growth.

In addition to soil nutrients, other factors such as temperature may also influence onion plant growth. Little onion plant growth was observed during the first 60 DAT probably because air temperatures were low. Growth of sweet onion plants is more active at an air temperature of ≈ 15 °C (unpublished data).

Foliar and bulb mineral nutrients. In Georgia, sweet onion foliar concentrations of N, Ca, and S were reported to augment with increasing organic fertilization rates (Boyhan et al., 2007). In a study using inorganic fertilization, foliar N of mature sweet onion plants (at harvest time) increased from a concentration of 1.5% with a fertilizer rate of 100 kg·ha⁻¹ N to a concentration of 3.2% with a rate of 300 kg·ha⁻¹ N; bulb N also increased with increasing N rate (Díaz-Pérez et al., 2003). In the present study, foliar N (mean = 1.03%) and Ca of mature plants decreased by increasing the organic fertilization rate. The N concentration in plants has been found to increase when plant

Table 2. Mineral nutrient concentration in mature sweet onion bulbs as influenced by organic fertilization rate. Bulbs were sampled immediately after harvest. Nitrogen was provided by a commercial organic fertilizer [microSTART60 (3–2–3); Perdue AgriRecycle, LLC]. Tifton, GA, Winter of 2013 and 2014.

	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	B (mg·kg ⁻¹)	Fe (mg·kg ⁻¹)	Cu (mg·kg ⁻¹)	Mn (mg·kg ⁻¹)	Zn (mg·kg ⁻¹)
N (kg·ha ⁻¹) ^a											
0	1.79	0.450	2.32	0.585	0.180	0.240	22.5	80.8	4.76	128.8	16.3
60	1.62	0.458	2.06	0.685	0.220	0.222	24.9	75.0	3.61	129.3	11.4
120	1.61	0.527	2.25	0.653	0.250	0.227	25.5	75.0	4.78	190.3	16.0
180	1.66	0.422	2.11	0.587	0.228	0.222	24.0	73.2	3.49	167.4	12.7
240	1.73	0.373	1.98	0.698	0.297	0.197	24.4	74.2	3.45	198.2	13.8
Significance ^b											
L	0.803	0.128	0.136	0.411	0.0004	0.056	0.514	0.328	0.011	0.002	0.399
Q	0.194	0.040	0.332	0.716	0.002	0.150	0.425	0.507	0.042	0.010	0.531

^aK/S = Rate (kg·ha⁻¹) of K and S applied as potassium thiosulfate.

^bL = linear; Q = quadratic response.

Fig. 5. Accumulation of nitrogen (A), phosphorus (B), potassium (C), calcium (D), magnesium (E), and sulfur (F) in sweet onion plants (shoot + bulb) as influenced by organic fertilization rate. Nitrogen was provided by a commercial organic fertilizer [microSTART60 (3–2–3); Perdue AgriRecycle, LLC]. Tifton, GA, Winter of 2013 and 2014.

development is constrained by environmental factors such as nutrients, water, or temperature (Barker and Bryson, 2007).

Foliar N and K (mean = 1.37% K) concentrations (Fig. 3A and C) were low probably because leaf samples were collected late in the season. At sampling time, plants displayed leaf chlorosis even in the highest organic fertilization rate. Our late leaf sampling may have underestimated the status of some of the nutrients. For fertilizer purposes, it is typically recommended to sample leaves during the period of active plant growth when there is an active nutrient demand (Römheld, 2012). In addition, the decreased foliar concentrations of N and Ca with increasing organic fertilization rates suggest the presence of a dilution effect associated with the increased plant growth (Fig. 2A and B). Foliar concentrations of N, K, Ca, Mg, and S were low whereas those of P were within the sufficiency range for onion whole tops from production fields at the 1/2 growth stage to maturity is 4.50% to 5.50% (N), 0.31% to 0.45% (P), 3.5% to 5.0% (K), 1.5% to 2.2% (Ca), 0.25% to 0.40% (Mg), and 0.50% to 1.0% (S) (Bryson and Mills, 2014). To our knowledge, there is no information about nutritional recommended levels for sweet onions under organic systems.

Chlorophyll indices were lowest for the unfertilized control for most of the season (Fig. 6A and B). Starting at ≈70 DAT, when plants started to grow more rapidly because of increased temperatures (Fig. 1) and, thus, have high N demand, plants at 60 kg·ha⁻¹ N showed reduced CI values compared with plants at higher organic fertilization rates, indicating the presence of low leaf N concentrations. At the end of the season, all fertilization treatments had similar CI values, consistent with the suggestion of low N soil levels occurring at the end of the season. The increasing CI values after JD 90 in the unfertilized treatment was probably more a result of increased leaf thickness than of augmented leaf N. Leaf thickness may affect the CI readings (Díaz-Pérez, 2013; Li et al., 2011). Leaf thickness has been found to increase under stress conditions, including nutrient stress (Larcher, 1995). Although leaf thickness was not measured in the present

Fig. 6. Sweet onion leaf chlorophyll indices during the growing season in response to organic fertilization rate in the 2013 (A) and 2014 (B) growing seasons. Tifton, GA. Nitrogen was provided by a commercial organic fertilizer [microSTART60 (3–2–3); Perdue AgriRecycle, LLC].

study, leaf thickness probably increased in the unfertilized treatment.

As in other crops, leaf N levels decrease as the season progresses because leaf N is translocated to other plant parts (Osaki and Shinano, 2001). Observation of nutrient deficiencies late in the season indicates that the preplant application of organic fertilizer, regardless of the application rate, was sufficient to cover plant nutritional needs only partially and that supplemental applications of fertilizer after midseason may be necessary. The degree of leaf chlorosis was particularly severe at the low organic fertilization rates. Plants at low organic fertilization rates started

to display leaf chlorosis ≈ 4 weeks before harvest. Plants fertilized organically, regardless of the rate, showed more chlorotic foliage compared with plants (same cultivar and planted the same day) of the adjacent K and S fertilizer study (Díaz-Pérez et al., 2016).

High application rates of organic fertilizer (above those required by the crop) may have resulted in nutrient leaching because it is unlikely that the onion crop used many of the nutrients available early in the season. In sandy loam soils such as that of this study, high N fertilization rates have been associated with increased soil leaching. Leaching of N and other nutrients, such as K, Mg, B,

Fig. 7. Agronomic efficiency of nitrogen (A) and marginal yield (B) of sweet onion plants as influenced by organic fertilization rate. Nitrogen was provided by a commercial organic fertilizer [microSTART60 (3–2–3); Perdue AgriRecycle, LLC]. Tifton, GA.

and S, in light soils may occur with the use of high rates of either inorganic or organic fertilizers (Simonne et al., 2010). Thus, split applications of organic fertilizers may be recommended to reduce nutrient leaching.

With respect to foliar micronutrients, except for Cu that increased with increasing organic fertilization rate, other micronutrients showed little response to organic fertilization rate (Fig. 4A–E). This observation suggests that the concentration of most micronutrients in the soil before organic fertilizer application was sufficient to satisfy the needs of onion plants. At all fertility rates, foliar concentrations of Mn and Zn were within the sufficiency range whereas those of B, Cu, and Fe were below the sufficiency range. Sufficiency ranges for foliar micronutrients are 22–60 $\text{mg}\cdot\text{kg}^{-1}$ B, 15–35 $\text{mg}\cdot\text{kg}^{-1}$ Cu, 60–200 $\text{mg}\cdot\text{kg}^{-1}$ Fe, 50–250 $\text{mg}\cdot\text{kg}^{-1}$ Mn, and 25–100 $\text{mg}\cdot\text{kg}^{-1}$ Zn (Bryson and Mills, 2014).

The impact of fertilization method on the accumulation of bulb nutrients is not fully understood. Application of humic acids was found to result in increased concentrations of bulb P (0.40%), K (1.17%), and Mg (0.32%) (Bettoni et al., 2016). In a hydroponic study, sweet onion bulb N levels were found to increase with N fertility and decrease slightly with S availability whereas bulb P levels

responded linearly to N fertility. Bulb S content was found to decrease with decreasing S and N fertility (Coolong et al., 2004). In another report, the addition of nutrients via soil or foliar biofertilizer was unable to supply the required nutrients and was responsible for generating imbalances which decreased the growth and development of the onion crop (Menezes Júnior et al., 2013). The mean mineral nutrient concentrations of onion bulbs under organic fertilization in the present study differed compared with the bulb nutrient concentrations under inorganic fertilization of the K and S study (Díaz-Pérez et al., 2016). Bulb N (1.84% vs. 2.00%), S (0.22% vs. 0.48%), and Zn (14 vs. 61 mg·kg⁻¹) concentrations were lower whereas concentrations of P (0.45% vs. 0.30%), K (2.14% vs. 1.24%), Ca (0.64% vs. 0.25%), Mg (0.24% vs. 0.10%), B (24 vs. 17 mg·kg⁻¹), Fe (76 vs. 40 mg·kg⁻¹), and Mn (163 vs. 141 mg·kg⁻¹) were higher in this study compared with the K and S study, indicating that utilization of organic fertilization resulted in more mineral nutrient-rich bulbs. In addition, the bulb concentrations of mineral nutrients of this study were lower for P, and higher for K, Ca, Mg, S, Cu, Mn, and Zn compared with those of cultivar Texas Early Grano (Galdon et al., 2008). Comparisons of mineral nutrient composition in onion are complex because the nutrient accumulation may be influenced by cultivar, environment, and agronomic practices.

The AEN decreased with increasing N rate (Fig. 7A) and there is a minimum AEN value that must be exceeded to make N fertilization profitable. This minimum is equal to the ratio of N price to crop price. The use of high application rates of organic fertilizers early in the season (as carried out in the present study) may result in high N leaching with the concomitant economic and environmental impacts. Low nutrient use efficiencies with organic fertilizers may occur because of the poor understanding of the mineralization rate of nutrients from organic fertilizers (Hartz and Johnstone, 2006). The present study was not intended to provide information about the N mineralization over the season; this information, however, is necessary to design efficient organic fertilization programs that minimize N loss.

In conclusion, onion plant growth increased with increasing organic fertilizer rate probably because of augmented soil nutrient levels (N, primarily). Observation of nutrient deficiencies late in the season even at high organic fertilization rates indicates that pre-plant application of organic fertilizer was sufficient to cover plant nutritional needs only partially and that supplemental fertilizer applications later in the season may be necessary. High application rates of organic

fertilizer (above those required by the crop) may have resulted in significant N leaching because it is unlikely that the crop used most of the N that was mineralized during the season. Bulb concentrations of P, K, Ca, Mg, S, B, Fe, Cu, and Mn were higher than the reported values under inorganic fertilization, indicating that utilization of organic fertilizers may result in mineral nutrient-rich bulbs.

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