Exploring the Potential of Lettuce (*Lactuca sativa* L.) as an Early Crop in Florida's Sandy Soils

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Abstract. Lettuce (*Lactuca sativa* L.) is planted in Florida starting late fall at the end of September and continuing through the last harvest in May. In recent years, the season has shortened because of warm temperatures and weather-related events, such as rainfall at the beginning and the end of the season. During the transition between summer production in the Western U.S. lettuce season and the beginning of Florida's winter production, there may be shortages of lettuce and other leafy vegetables in U.S. East Coast markets. In this research, we evaluated a set of lettuce breeding lines and cultivars in both sand and muck soils and a subset of romaine lettuces to determine whether lettuce planted in Florida's sandy soils could help meet the supply shortage in the delay between the Western and Eastern U.S. lettuce seasons. Significant genetic variation and genotype $\times$ environment (G $\times$ E) interactions were observed among lettuce genotypes when planted in both sand and muck soils, suggesting that lettuce cultivars should be adapted and bred specifically for sandy soils. Romaine and butterhead lettuce lines produced higher yield in sandy soils; a particular romaine breeding line (BG18-0588) had good yield and less heat-related disorders when planted in warmer temperatures. Producing lettuce in sandy soils may have a higher production cost because of additional specific practices such as transplant production, plastic mulch, and fertigation, but these costs may be offset by increased productivity due to better weed control and nutrient timing. However, a future analysis should be conducted to elucidate the economic feasibility of producing lettuce in sandy soils.

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OM by dry weight) and ample supply of nutrients (Janardhanan and Daroub, 2010; Wright and Hanlon, 2019). Despite great fertility, these soils are constantly subjected to wind erosion and OM decomposition by microorganisms (Bhadha et al., 2020; Rodriguez et al., 2020) and have a large seedbank of problematic weed species (Cantliffe and Karchi, 1992; Otero and Wright, 2013; Robles et al., 1997).

Warmer temperatures affect the lettuce crop in muck soils. Historically, lettuce production in the EAA started with the first plantings in September and ended in May with the last harvests. Currently, the warmer temperatures experienced in the EAA have shortened the lettuce season to planting in late September and harvesting between mid-March to the beginning of April. In the future, growers may need to plant lettuce earlier in the season in northern and central Florida because northern latitudes present cooler temperatures than those observed in the EAA. The expansion of lettuce cultivation into northern Florida regions has the potential to extend the growing season and allow producers to supply lettuce to the market during shortages (Cantliffe and Karchi, 1992). However, soils in northern regions contain much higher sand content and may require adapted lettuce cultivars. Current lettuce cultivars planted in Florida have been specifically bred for muck soils since lettuce production mainly occurs in the EAA.

Soils found in central and northern Florida are derived from sandy marine sediments and, therefore, present sandy texture (Mylavarapu et al., 2019). Florida's sandy soils are acidic and highly weathered, as a result of high temperatures and abundant rainfall characteristic to these regions. Several agricultural commodities are planted in Florida's sandy soils including potato, cabbage, watermelon, melon, tomato, squash, sweet corn, strawberry, and bell pepper (Freeman et al., 2019). Lettuce is not currently planted in sandy soils but may serve as a potential early crop for growers located in central and northern areas of Florida, where sandy soils predominate.

Planting lettuce in sandy soils earlier than when planting begins in muck soils will have the risk of facing warmer temperatures. Therefore, lettuce yield may be negatively affected by less marketable heads, the presence of bolted plants, and the appearance of disorders such as tipburn (Jenni et al., 2013). Bolting is a process in which the lettuce stem elongates after the transition from vegetative to reproductive stage that negatively affects lettuce marketability and is strongly influenced by environmental factors, such as temperature and photoperiod, as well as genetic variation (Hao et al., 2018). Tipburn is a physiological disorder commonly associated with localized calcium deficiency and leaf margin necrosis that occur in newly formed leaves and is exacerbated by warm temperatures and high relative humidity that inhibits calcium translocation from evapotranspiration (Barta and Tibbits, 2000; Jenni et al., 2013).

Lettuce (*Lactuca sativa* L.) is one of the most valuable vegetables in the world. The United States ranks as the second largest lettuce producer after China, harvesting $\approx 105,000$ ha worth \$3.5 billion in 2019 [Food and Agriculture Organization of the United Nations, 2020; U.S. Department of Agriculture National Agricultural Statistics Service Information (USDA NASS), 2019]. Florida accounts for $\approx 3.5\%$ of the U.S. total lettuce production, corresponding to ≈ 3700 harvested ha (USDA NASS, 2019). Most of this production is concentrated in the Everglades Agricultural Area (EAA) (Sandoya and Lu, 2020), where lettuce is planted as a rotational crop between sugarcane (*Saccharum* spp. interspecific hybrids) cycles (Castillo and Wright, 2008).

The EAA is an artificially drained area (283,300 ha) renowned for tremendous agricultural productivity. Soils in the EAA, often called "muck" (Histosols), contain high organic matter (OM) (typically 65% to 85%

One limitation for planting lettuce in sandy soils is the need of using transplants because earlier direct plantings in Florida may not be possible due to warmer soil conditions. Although transplanting may increase the cost of production, this expense might be offset by the benefits associated with using plastic mulch and drip fertigation required for production in sandy soils. Both help reduce weed pressure (Birthisel et al., 2019; Cantliffe et al., 1997), result in more efficient application of water and fertilizer (Alkhader et al., 2019), increase soil moisture near rhizosphere areas (Mkhabela et al., 2019), and permit more efficient control of soilborne pathogens (dos Santos et al., 2014).

Lettuce is widely planted in different soil types and in soilless systems; however, there is limited information on lettuce production in sandy soils of Florida. In this research, we studied the adaptability of lettuce to sandy soils using a group of cultivars and breeding lines with no prior testing in Florida's sandy soils. As some lettuce lines performed better in sand, we investigated whether selection conducted in muck soils would be effective in sandy soils by determining the G×E interactions. Lastly, we subjected four selected romaine lines to early-season plantings with the goal of evaluating whether the current lettuce production window has the potential to be lengthened by planting in cooler northern regions with sandy soils.

Materials and Methods

Initial assessment of lettuce cultivars and breeding lines in sandy vs. muck soils

Plant material. Twenty-six lettuce cultivars and breeding lines, consisting of 11 cos (romaine), 10 iceberg (crisphead), 4 butterhead, and 1 green leaf, were used in an initial assessment conducted in four individual experiments (Table 1). In this initial assessment, 11 accessions were experimental breeding lines defined as the breeding base of the University of Florida's Institute of Food and Agriculture Sciences (UF/IFAS) Lettuce Breeding Program and are named with numbers. Eleven were commercial cultivars with formal names that are currently used by growers at the EAA, and the other four were cultivars developed by the UF/IFAS lettuce breeding program that were previously used as commercial cultivars.

Sandy soil experiments. The first two experiments (Expts. 1 and 2) were conducted on sandy soils in commercial production fields in 2017 and 2018 in Loxahatchee, FL (Table 2). Lettuce seeds were germinated at the UF/IFAS Everglades Research and Education Center (EREC) in 242-cell seedling trays filled with commercial substrate (Sun Gro Horticulture Professional Growing Mix; Sun Gro Horticultural Products, Bellevue, WA). Seedlings, which were sown on 6 Dec. 2017 for Expt. 1 and on 27 Sept. 2018 for Expt. 2, were grown for 5 to 6 weeks before transplanting in 1.14 m × 178.30 m beds covered with white polyethylene mulch. Seedlings were transplanted in Riviera fine

sand (loamy, siliceous, active, hyperthermic Arenic Glossaqualfs) on 19 Jan. 2018 for Expt. 1 and in Holopaw fine sand (loamy, siliceous, active, hyperthermic Grossarenic Endoaqualfs) on 6 Nov. 2018 for Expt. 2 on a 4-row bed layout. Each plot was 4.57 m long and consisted of a cultivar/line planted in two rows with a 0.20 m spacing between rows and a 0.30 m spacing between plants (except in the first experiment where spacing between plants was 0.15 m). Pest and disease management were applied according to the industry standards and fertigation was supplied via two drip lines.

Muck soil experiments. Two field experiments (Expts. 3 and 4) were planted on muck soils on 23 Oct. 2018 and on 5 Mar. 2019, respectively (Table 2). The trial in 2018 was established on Dania muck (euic, hyperthermic Lithic Haplosaprists) at the EREC, in Belle Glade, FL. Field fertilization consisted of a preplanting application of 560 kg·ha⁻¹ of ammonium polyphosphate (11N–16.2P–0K; Wedgworth's Inc., Clewiston, FL) plus two post-planting split applications of 4.5 kg·ha⁻¹ of multipurpose fertilizer (20N–8.7P–16.6K; Plant Foods Inc., Vero Beach, FL), following soil test recommendations for lettuce crops

from the UF/IFAS Soil Testing Laboratory at the EREC. Pests and diseases were managed following the industry standard recommendations of the Vegetable Production Handbook of Florida (Kanissery et al., 2019), and irrigation was provided as needed throughout the crop cycle using a combination of overhead (establishment) and seepage (afterward) irrigation. The trial in 2019 was performed on Terra Ceia muck (euic, hyperthermic Lithic Haplosaprists) in a commercial leafy production field located near Belle Glade, FL. Field fertilization, weed management, and irrigation were performed following the standard procedures adopted by the commercial farm. Both experiments were direct seeded on 0.15-m raised beds. Plots consisted of two rows per cultivar/line and were 6.1 m long. At the four-leaf stage, seedlings were thinned to a 0.30 m in-row spacing.

Additional screening of romaine lettuce in North Florida sandy soils for earlier planting

Plant material. Three romaine lettuce breeding lines from the UF/IFAS Lettuce Breeding Program and one romaine cultivar were tested in subsequent experiments;

Table 1. Breeding lines and cultivars selected for experiments in muck and sandy soils, morphological types (butterhead, iceberg, leaf, and romaine), breeding status, and breeder.

Breeding line/cultivar	Type	Status	Breeder
Initial assessment			
60176	Butterhead	Breeding line	UF/IFAS
60178	Butterhead	Breeding line	UF/IFAS
Floribibb ^z	Butterhead	Cultivar	UF/IFAS
Palmetto ^y	Butterhead	Cultivar	Private company
60167	Iceberg	Breeding line	UF/IFAS
60168	Iceberg	Breeding line	UF/IFAS
60171	Iceberg	Breeding line	UF/IFAS
60172	Iceberg	Breeding line	UF/IFAS
60180	Iceberg	Breeding line	UF/IFAS
Belle Glade ^y	Iceberg	Cultivar	Private company
Chosen ^y	Iceberg	Cultivar	Private company
Flagler ^y	Iceberg	Cultivar	Private company
Floricrisp 1265 ^z	Iceberg	Cultivar	UF/IFAS
Lantana ^y	Iceberg	Cultivar	Private company
RSX743 ^y	Leaf	Breeding line	Private Company
60166	Romaine	Breeding line	UF/IFAS
60182	Romaine	Breeding line	UF/IFAS
60184	Romaine	Breeding line	UF/IFAS
70096	Romaine	Breeding line	UF/IFAS
Floricos 83 ^z	Romaine	Cultivar	UF/IFAS
Hialeah ^y	Romaine	Cultivar	Private company
Homestead ^y	Romaine	Cultivar	Private company
Manatee ^y	Romaine	Cultivar	Private company
Okeechobee ^y	Romaine	Cultivar	Private company
Sawgrass ^y	Romaine	Cultivar	Private company
Terrapin ^z	Romaine	Cultivar	UF/IFAS
Follow-up experiments			
60182	Romaine	Breeding line	UF/IFAS
70096	Romaine	Breeding line	UF/IFAS
BG18-0588 ^x	Romaine	Breeding line	UF/IFAS
Terrapin ^z	Romaine	Cultivar	UF/IFAS

^zLettuce cultivars developed by the University of Florida/Institute for Food and Agricultural Services (UF/IFAS) lettuce breeding program (Guzman and Raleigh, 1984; Guzman and Zitter, 1983, 1984; Sandoya and Lu, 2020). Cultivar Terrapin is currently under Plant Variety Protection.

^yCommercial lettuce cultivars currently used by growers in Florida and developed by private seed companies.

^xModern advanced breeding line currently in development by UF/IFAS lettuce breeding program.

romaine lettuce was chosen based on their overall yield in sandy soils in the previous trials. This group included ‘Terrapin’ and breeding line 60182, which had a better performance in the initial assessment; the breeding line 70096 that had an equal performance in muck and sandy soils; and an experimental line BG18-0588 (Belle Glade 2018 line 588) was included because it has been previously observed to perform well in warmer environments with little tipburn (G. Sandoya, personal observations) (Table 1).

Experiment description. In 2019, two experiments were conducted at the UF/IFAS Hastings Agricultural Extension Center in Hastings, FL (located ≈ 350 km north of the EAA), to test the performance of the four romaine accessions in early season planting experiments on sandy soils (Table 2). The soil at the experimental sites was Ellzey fine sand (sandy, siliceous, hyperthermic Arenic Endoaqualls). Seedlings of each genotype were produced by Speedling Inc. at two different nursery locations (Sun City, FL, and Blairsville, GA) to test the effect of temperature differences during seedling establishment. Seeds of romaine lettuce were sown in both nurseries on 15 Aug. 2019 for the first experiment (E5) and on 26 Aug. 2019 for the second experiment (E6). Seedlings from the two nurseries were grown for 3 weeks before being manually transplanted into white polyethylene mulch beds on 11 Sept. 2019 and 1 Oct. 2019 for E5 and E6, respectively (Table 2).

Each treatment was defined as the combination of one breeding line and one seed-

ling source. Each plot consisted of a 4-row plastic mulched bed (1.22 m wide and 10 m long) containing two drip lines for nutrient and water application via fertigation. In each experiment, field fertilization consisted of a preplanting application of $1400 \text{ kg}\cdot\text{ha}^{-1}$ of fertilizer (4N–3.5P–3.3K). In the first experiment, fertigation was initiated 6 d after the lettuce seedlings were transplanted and continued for 6 weeks, with one application occurring each week. In the second experiment, the first fertigation occurred 1 d before transplanting and continued for another 6 weeks with one application per week. In both trials, each fertigation event comprised the application of $28 \text{ kg}\cdot\text{ha}^{-1}$ of N and $23.2 \text{ kg}\cdot\text{ha}^{-1}$ of K using a liquid fertilizer blend (8N–0P–6.6K). In total, each experiment received $224 \text{ kg}\cdot\text{ha}^{-1}$ of N, $48.9 \text{ kg}\cdot\text{ha}^{-1}$ of P, and $185.9 \text{ kg}\cdot\text{ha}^{-1}$ of K on pre- and postplanting applications. Irrigation was provided three times/day for 10 min each event using two drip lines with a 30 cm emitter spacing and a $\approx 45 \text{ L}\cdot\text{h}^{-1}$ output. Under rainfall events of more than 12 mm, the irrigation was interrupted for 1 d.

Data collection. In all six trials, plants were evaluated by lettuce type at harvest maturity, which varied from 57 to 79 d after sowing, based on the maturity of controls that included cultivars Palmetto for butterhead, Chosen for iceberg, and Hialeah or Okeechobee for romaine in Expts. 1 through 4 and Terrapin for romaine in Expts. 5 and 6. In Expts. 1 through 4, harvest started with leaf types butterhead and romaine and was followed by iceberg 1 week later (Table 2). Four

traits were measured during the execution of these experiments: head weight (HW) was measured on 10 randomly harvested lettuce heads per plot and expressed as grams per head; marketability was estimated by counting the number of total plants per plot and the number of heads as the percentage of lettuce heads that would meet market requirements, such as expected head formation, uniformity and heads free of visual diseases and disorders; tipburn incidence was recorded post-harvest by slicing 10 heads in half to observe the inner whorl; and bolting incidence was estimated by counting the total number of plants in each plot that presented stem elongation.

Experimental design and statistical analysis. Expts. 1 through 4 were arranged following a randomized complete block design (RCBD) with three replications. Statistical analyses were calculated using the GLIMMIX procedure in SAS software, Version 9.4 (SAS Institute Inc., Cary, NC). The HW, tipburn, and marketability data were grouped according to each lettuce type before being subjected to analysis of variance (ANOVA). Due to the absence of bolting in most lettuce accessions grown in muck soil experiments, bolting data were not analyzed. The factors soil, genotype, and soil $\times$ genotype interaction were considered fixed effects, whereas block nested within experiment was considered as random effect. Since the leaf type was represented by a single cultivar, soil was the only fixed effect used in the respective model.

Expts. 5 and 6 conducted in Hastings, FL, followed a RCBD with three replications. HW and bolting data of all four romaine

Table 2. Number, location, soil type, number of cultivars/breeding lines tested, and planting date conducted in this research.

Expt.	Location	Soil type	Cultivars/breeding lines	Sowing	Transplanting	Harvest	Expt.
Initial assessment							
Sand 2017	Loxahatchee	Sand	26	6 Dec. 2017	19 Jan. 2018	23 Feb. 2018 ^z	1
Sand 2018	Loxahatchee	Sand	26	27 Sept. 2018	6 Nov. 2018	5 Dec. 2018 ^z	2
Muck 2018	Belle Glade	Muck	26	23 Oct. 2018	—	28 Dec. 2018 ^z	3
Muck 2019	Belle Glade	Muck	26	5 Mar. 2019	—	1 May 2019 ^z	4
Early planting							
Sand 2019	Hastings	Sand	4	15 Aug. 2019	11 Sept. 2019	29 Oct. 2019	5
Sand 2019	Hastings	Sand	4	26 Aug. 2019	1 Oct. 2019	4 Nov. 2019	6

^zActual date for harvest of butterhead, leaf and romaine lettuce; iceberg harvesting occurred ≈ 1 week later.

Table 3. Analysis of variance of head weight, marketability and tipburn of 26 lettuce cultivars and breeding lines planted in two experiments in sandy soils (Expts. 1 and 2) and two experiments in muck soils (Expts. 3 and 4) near Loxahatchee and Belle Glade, FL.

Source of variation	Head wt				Marketability				Tipburn			
	df _{num} ^y	df _{den} ^y	F value	P value	df _{num}	df _{den}	F value	P value	df _{num}	df _{den}	F value	P value
Soil	1	10.03	1.41	0.2617	1	6.95	31.68	0.0008	1	10.22	22.37	0.0008
Butterhead	1	10.05	6.21	0.0318	1	7	0.00	0.9974	1	10	15.50	0.0028
Iceberg	1	10.02	5.62	0.0392	1	7.069	85.42	<0.0001	1	10	4.77	0.0539
Leaf ^z	1	7.092	1.03	0.3433	1	5	41.90	0.0013	1	10	1.00	0.3409
Romaine	1	10.40	0.40	0.5396	1	7.707	15.37	0.0056	1	10	16.15	0.0024
Genotype	25	239.2	5.84	<0.0001	25	166.1	4.90	<0.0001	25	239.6	3.61	<0.0001
Butterhead	3	29.17	10.01	0.0001	3	21	8.90	0.0005	3	30	2.31	0.0962
Iceberg	9	89.03	1.30	0.2472	9	60.58	4.92	<0.0001	9	89	3.34	0.0014
Romaine	10	92.72	4.20	<0.0001	10	68.11	2.49	0.0132	9	85	0.53	0.8463
Genotype $\times$ soil	25	239.2	4.55	<0.0001	25	166.1	3.63	<0.0001	25	239.6	3.17	<0.0001
Butterhead $\times$ soil	3	29.17	11.86	<0.0001	3	21	2.97	0.0553	3	30	2.31	0.0962
Iceberg $\times$ soil	9	89.03	2.96	0.0040	9	60.58	1.69	0.1121	9	89	0.5	0.8740
Romaine $\times$ soil	10	92.72	3.78	0.0003	10	68.11	2.49	0.0099	9	85	0.53	0.8463

^zDifferences among genotypes and the interaction with soil factor was not calculated for leaf type as only one cultivar was used during the execution of this experiment.

^ydf_{num} is the degree of freedom of numerator, df_{den} is the degree of freedom of denominator.

accessions were subjected to ANOVA using the GLIMMIX procedure in SAS software. The factors genotype, nursery, and experiment and all possible interactions were considered as fixed effects, whereas block nested within experiment was considered as random effect.

In all experiments, least square means of each treatment and 95% confidence intervals (CIs) were generated using the *lsmeans* statement in PROC GLIMMIX. Significant differences between treatments were obtained using Fisher's least significant difference test at a level of significance of $P < 0.05$ using the PDMIX800 macro (Saxton, 1998).

G×E analysis. A G×E analysis was conducted to assess the HW variability of lettuce cultivars and lines across different environments and soil types. Each environment was defined as the combination of a location and a year. The HW of lettuce genotypes were subjected to ANOVA to estimate the effects of genotype, environment, and G×E using the GGEbiplot software (<http://www.ggebiplot.com/>). The GGE biplots were constructed following the equation presented by Yan et al. (2000):

$$Y_{ij} - \mu - \beta_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \varepsilon_{ij},$$

where Y_{ij} is the mean for the i^{th} genotype in the j^{th} environment, μ is the grand mean β_j is the main effect of environment j , λ_1 and λ_2 are the singular values of the first and second principal components, ξ_{i1} and ξ_{i2} are the PC1 and PC2 scores, respectively, for genotype i^{th} , η_{j1} and η_{j2} are the eigenvectors for the j^{th} environment for PC1 and PC2, and ε_{ij} is the residual error term.

Results and Discussion

Horticultural characteristic in lettuce planted in muck versus sandy soils. The yield of lettuce planted in sandy soils was statistically the same as in muck soils ($P = 0.2617$), as expressed by HW (Table 3). A small difference in HW is noted between sandy and muck soils (Fig. 1), however, HW was clearly affected by experiment. Temperature is unlikely responsible for these differences because temperatures were similar during the execution of the experiments; maximum/minimum temperatures varied from 26 °C/15 °C to 29 °C/16 °C (Table 4). These temperatures were near the acceptable range for lettuce production because lettuce is well adapted to temperatures between 18 to 25 °C during daytime and 10 to 15 °C at nighttime (Hayes, 2018). Instead, other factors likely influenced the differences found in the overall HW for these four experiments. Muck experiments were planted at two locations; the first muck experiment was planted in an experimental farm at the EREC, and the second was planted in a commercial field located in the EAA. Although both locations are nearby, commercial fields have better crop management practices including a more efficient weed control and fertilization that may have influenced HW.

HW in lettuce varied among morphological types with respect to soil types. In butterhead

Fig. 1. Least square Means (LSM) of head weight (HW) averaged by experiment regardless of lettuce type in four experiments conducted between 2017 and 2019 in two soil types, muck and sand near Loxahatchee (sand) and Belle Glade (muck), FL. Least significant differences are presented by experiment (LSD = 39.2; $P = 0.05$).

Table 4. Monthly average of medium, minimum, and maximum temperature and total monthly precipitation during the execution of experiments in this research in Loxahatchee, Belle Glade, and Sun City, FL, and in Blairsville, GA.

Location	Yr	Expt.	Month	Temperature (°C)			Precipitation (mm)
				Medium	Min	Max	
Loxahatchee, FL	2018	1	January	18	13	23	33.27
		1	February	23	18	29	12.19
		2	November	23	18	29	26.92
		2	December	20	15	26	23.88
Belle Glade, FL	2017	1	December	18	12	26	43.43
		—	—	—	—	—	—
	2018	1	January	16	11	23	18.80
		—	February	21	15	29	6.10
		2	September	26	22	33	128.02
		2 and 3	October	25	20	32	19.56
		2 and 3	November	22	16	28	44.70
		3	December	19	13	26	34.29
	2019	4	March	21	15	28	34.04
		4	April	23	17	30	39.37
		4	May	25	20	32	122.17
Blairsville, GA	2019	5 and 6	August	24	17	30	94.74
		5 and 6	September	23	15	31	8.38
Sun City, FL	2019	5 and 6	August	27	23	33	243.84
		5 and 6	September	27	22	33	31.50
Hastings, FL	2019	—	August	27	23	33	139.95
		5	September	26	21	32	110.24
		5 and 6	October	24	20	29	105.41
		6	November	17	11	23	83.06

^zWeather data collected from the closest Florida Automated Weather Network station, located in Balm, FL (≈25 km from the nursery in Sun City, FL).

lettuce, significant differences ($P = 0.0318$) were found for HW between muck and sand plantings (Table 3; Fig. 2). Romaine and leaf lettuce showed a slightly higher HW in sand compared with muck soils, but these differences were found to be nonsignificant ($P = 0.5396$ and $P = 0.3433$, respectively) (Table 3; Fig. 2). The results of this research indicate that

lettuce, specifically romaine and butterhead types, can be planted in sandy soils if an adequate fertilizer program, irrigation, and practices that might include the use of microorganisms as biostimulants are used. A proper fertilization program along with the application of biostimulants may improve the yield of lettuce grown in sandy soils up to 85%, as

previously observed in Brazil (Moraes et al., 2018).

Furthermore, the findings of this study are consistent with lettuce's ubiquitous adaptation, ranging from clay soils in Western United States, to soilless systems in protected structures (hydroponic, aeroponic, aquaponic), and more specifically adapted to muck soils in Florida's subtropical EAA since the 1940s (Parkell et al., 2015; Sandoya, 2019; Sandoya and Lu, 2020). Breeding lines and cultivars tested in this research were improved for this latter environment, which inherently demonstrates their adaptability to warmer environments with unique soil properties (Guzman and Raleigh, 1984; Guzman and Zitter, 1983, 1984; Mikel, 2013). In fact, several releases from the UF/IFAS lettuce breeding program, including iceberg cultivars South Bay, Raleigh, Floricrisp 1265, and Floricrisp 1366; and romaine cultivars Tall Guzman, and Floricos 83 (Guzman, 1984, 1986; Guzman and Raleigh, 1984; Guzman and Zitter, 1983; Sandoya and Lu, 2020), are planted in soils other than muck and have been adapted to several geographic locations, soil types, and production systems (Dufault et al., 2009; Mikel, 2013; Simko, 2019; Soundy et al., 2005). Therefore, it is not surprising that the crop may also be cultivated in sandy soils despite low fertility, because adding adequate fertilizers to the lettuce crop has proven to successfully yield good marketable heads in greenhouse lettuce production (Sabat et al., 2015; Wiggins et al., 2020).

In addition, we evaluated genotypes for differences in HW within each lettuce type across both sandy and muck environments. Romaine ($P < 0.0001$) and butterhead ($P = 0.0001$) both had significant differences in genotype performance for HW when cultivated in the two soil types (Fig. 3; Table 3). Overall, lettuce cultivation in sandy soils resulted in a superior and significant HW compared with muck soils in several butterhead and romaine lettuce lines and cultivars (Fig. 4). For example, in butterhead lettuce, the breeding line 60176 and UF/IFAS cultivar Floribibb had higher HW in sand compared with muck. Regarding romaine types, the formerly released UF/IFAS cultivar, Floricos 83, and commercial cultivar Hialeah had a significantly higher HW in sandy soils compared with muck soils, whereas the UF/IFAS cultivar Terrapin and breeding line 70096 had a similar HW in both soil types. Other cultivars and breeding lines had a higher and nonsignificant HW in muck soil plantings (Fig. 4). The genetic variation within these UF/IFAS butterhead and romaine cultivars and breeding lines could be considered as the parental material for potential improvement programs targeted for sandy soils.

The practice of planting iceberg lettuce in Florida's sandy soils has previously proven successful (Cantliffe and Karchi, 1992; Cantliffe et al., 1997). However, in this research, iceberg lettuce HW was significantly higher in muck soils compared with sand ($P =$

Fig. 2. Least square means (LSM) of head weight (HW) averaged by lettuce type in four experiments conducted between 2017 and 2019 in two soil types, muck and sand near Loxahatchee (sand) and Belle Glade (muck), FL. Least significant differences (LSD; $P = 0.05$) are presented for each type and experiment; butterhead (LSD = 94.4), iceberg (LSD = 151.5), leaf (LSD = 163.1), and romaine (LSD = 130.3).

Fig. 3. Least square means (LSM) of head weight (HW) averaged by lettuce cultivars in four experiments conducted between 2017 and 2019 in two soil types, muck and sand near Loxahatchee (sand) and Belle Glade (muck), FL. Least significant difference (LSD; $P = 0.05$) is presented for cultivar or breeding line (LSD = 86.21).

0.0392; Table 3) which is reflected in almost all the tested genotypes (Figs. 4 and 5). This difference might be due to differences in fertility requirements among the different lettuce types (Hochmuth et al., 2018). Iceberg lettuces tend to require higher amounts of zinc (Zn) and manganese (Mn) than romaine and butterhead types to maintain adequate fertility. Several studies have documented increases in dry mass of iceberg lettuce in response to the application of Zn and Mn to the crop (de Resende et al., 2005, 2008; Petrazzini et al., 2010; Yuri et al., 2006), or a decrease in dry mass of iceberg lettuce compared with leaf lettuce when grown in nutrient solutions containing suboptimal levels of Zn and Mn (Roosta et al., 2018).

Coincidentally, the relatively high pH (between 7.0 and 8.0) of EAA's muck soils tends to have a high binding affinity for trace elements, such as Zn and Mn, the bioavailability of which are often found in very low concentrations in soil solution (Hochmuth et al., 2018). Lettuce farmers tend to have well-established programs of foliar fertilization with the goal of supplying macro- and micronutrients throughout the crop cycles to compensate the low bioavailability of Zn and Mn. A complementary application of foliar fertilizers based on Zn and Mn may help explain the overall higher HW of iceberg lettuce in fertilized muck soils, and especially the higher iceberg HW in E4 conducted in a commercial production system. This

experiment was conducted on a commercial farm that continuously produces lettuce for at least 3 years, whereas E3 received no micro-nutrient applications during the experiment.

In this research, differences were identified between sandy and muck soils ($P = 0.0008$) and within the germplasm tested ($P < 0.0001$) for the percentage of marketable heads (Table 3). These differences were notable within each type and most accessions

had higher percentage of marketable heads when planted in sandy soils compared with muck (Table 5), which agrees with the previous report by White and Guzman (1979). Higher lettuce marketability grown in sandy soils may be associated with better growing conditions provided by the plastic mulching, including greater soil moisture retention, lower weed pressure, and localized and more frequent application of fertilizers and water

via drip tape. The cultivation of lettuce in bare soil confers less efficient control of weeds and fertilizer application. Weeds are among the major challenges for lettuce producers in muck soils due to the limited number of efficient herbicides labeled for lettuce (Odero and Wright, 2013). As a result, the weed interference in lettuce crops can lead to yield losses of 20% to 48%, which is inherently avoided in sandy soil production with plastic covered beds (Dittmar and Boyd, 2020; Santos et al., 2003).

Lettuce accessions grown in sandy soils had significantly higher incidence of bolting (data not shown), and very low bolting was registered in muck experiments. Romaine lettuces grown in sandy soils had a greater bolting percentage (35% on average) compared with muck soils (0%), with cultivars Terrapin, Okeechobee, Sawgrass, and the breeding line 60182 being the most affected (85%, 56%, 53%, and 52%, respectively; data not shown). Similarly, cultivar Floribibb (butterhead), breeding line 60176 (butterhead), RSX743 (leaf), and breeding line 60180 (iceberg) had high bolting percentages when grown in sand (59%, 70%, 51%, and 36%, respectively), but low percentage of bolted plants in muck soils ($\leq 10\%$; data not shown). Furthermore, two butterhead accessions (60178 and Palmetto), five icebergs (60167, 60172, Chosen, Lantana, and Flagler), and two romaine lettuces (60166 and Manatee) did not present bolting across all experiments (data not shown). These results demonstrate the presence of genetic

Fig. 4. Least square means (LSM) of head weight (HW) averaged by lettuce cultivars in four experiments conducted between 2017 and 2019 in two soil types, muck and sand near Loxahatchee (sand) and Belle Glade (muck), FL. Least significant difference (LSD; $P = 0.05$) is presented for soil type $\times$ genotype (LSD = 126.4).

Fig. 5. Least square means (LSM) of head weight (HW) averaged by lettuce cultivars in four experiments conducted between 2017 and 2019 in two soil types, muck and sand near Loxahatchee (sand) and Belle Glade (muck), FL. Least significant difference (LSD; $P = 0.05$) is presented for cultivar/line $\times$ experiment (LSD = 133.6).

Table 5. Least square means (LSM) of percentage of marketable heads and tipburn in 25 lettuce cultivars and breeding lines planted in two experiments each on muck and sandy soils near Loxahatchee (sand) and Belle Glade (muck), FL.

Cultivar/line	Marketability (%)					Tipburn (%)				
	Sand		Muck		Avg	Sand		Muck		Avg
	2017	2018	2018	2019 ²		2017	2018	2018	2019	
Butterhead										
60176	0	64	37	—	34	45	4	0	0	12
60178	0	42	59	—	34	62	25	0	0	22
Floribibb	100	78	59	—	79	0	0	0	0	0
Palmetto	100	82	79	—	87	48	0	0	0	12
LSD (G) ^y	24.6					16.9				
LSD (S) ^x	29.2					13.0				
LSD (E) ^w	33.8					15.4				
LSD (G×S) ^v	37.1					23.9				
LSD (G×E) ^u	32.9					27.5				
Iceberg										
60167	73	89	30	—	64	2	7	0	0	2
60168	30	91	17	—	46	0	11	0	0	3
60171	82	96	10	—	63	0	6	0	2	2
60172	50	86	26	—	54	2	0	0	0	0
60180	48	0	2	—	17	37	0	0	16	13
Belle Glade	72	80	20	—	57	0	3	0	0	1
Chosen	83	67	64	—	71	3	2	0	0	1
Flagler	83	97	55	—	78	0	0	0	0	0
Floricrisp 1265	90	76	25	—	64	3	0	0	0	1
Lantana	88	92	35	—	72	2	0	0	0	0
LSD (G)	20.7					6.0				
LSD (S)	11.7					3.0				
LSD (E)	12.6					3.5				
LSD (G×S)	29.2					8.5				
LSD (G×E)	28.7					9.6				
Leaf										
RSX743	100	100	48	—	83	0	2	0	0	1
LSD (S)	20.6					2.2				
LSD (E)	25.4					3.3				
Romaine										
60166	60	87	13	—	53	3	9	0	0	3
60182	65	76	57	—	66	0	2	0	—	1
60184	30	98	44	—	57	0	7	0	0	2
70096	63	100	66	—	76	12	4	0	0	4
Floricos 83	60	88	17	—	55	0	0	0	0	0
Hialeah	88	96	26	—	70	10	4	0	0	4
Homestead	70	94	38	—	67	0	10	0	0	3
Manatee	82	84	58	—	75	10	3	0	0	3
Okeechobee	95	96	44	—	78	0	2	0	0	1
Sawgrass	68	98	42	—	69	2	4	0	0	2
Terrapin	53	100	67	—	73	5	0	0	0	1
LSD (G)	18.1					4.8				
LSD (S)	22.0					2.3				
LSD (E)	13.1					3.4				
LSD (G×S)	28.3					6.8				
LSD (G×E)	27.8					9.8				
Environment	67	83	39			10	4	0	1	

²Data for marketability in this experiment was lost.

^yLeast significant difference (LSD; $P = 0.05$) for genotype (G).

^xLSD ($P = 0.05$) for soils (S).

^wLSD ($P = 0.05$) for environment (E).

^vLSD ($P = 0.05$) for G×S.

^uLSD ($P = 0.05$) for G×E.

variability for bolting among the lettuce germplasm tested in sand vs. muck, which may be in addition to temperature and photoperiod (environment) regardless of soil type (Hao et al., 2018; Holmes et al., 2019; Jenni and Yan, 2009). Furthermore, the higher incidence of bolting in sandy soils could be partially explained by the longer number of days from sowing to harvest in Expts. 1 and 2 compared with those conducted in muck soils (Expts. 3 and 4) (Table 2).

Tipburn was mostly found in sandy soil experiments rather than in muck soil experiments ($P = 0.0008$), especially in the 2017

experiment (Table 5), which was planted in December when temperatures were more suitable for lettuce production. Differences were also observed at the germplasm level ($P < 0.0001$; Table 3), which indicate genetic variability in the germplasm tested as previously reported (Jenni and Hayes, 2010; Ryder and Waycott, 1998). Although many values were minimal in this research, butterhead (60176 and 60178) and iceberg breeding lines (60180) were the germplasm with higher percentage of tipburn (Table 5). One iceberg breeding line (60172); two formerly released cultivars (Floribibb and Floricos 83)

of butterhead and romaine, respectively; and two iceberg commercial cultivars (Flagler and Lantana) produced no tipburn across all experiments (Table 5). The genetic variation identified for tipburn in lettuce is typically more distinct when planted in extremely warm environments (Lafta et al., 2017), but these results also demonstrate that G×E interaction for tipburn may exist for different soil types.

Genotype × environment interaction for HW in lettuce. This research was conducted in muck and sandy soils by planting lettuce breeding lines and cultivars that have been

no interaction of each of the studied types $\times$ soil was significant ($P > 0.05$) for tipburn, despite the overall significant interaction among all lettuce types (Table 3). If an interaction plays a role in HW, this might be a crossover type interaction because correlations were weak and nonsignificant ($P > 0.05$) among experiments (Expts. 1–4), except for experiments Expts. 1 and 2 ($r = 0.26$; $P = 0.0292$) and Expts. 1 and 4 ($r = 0.29$; $P = 0.0128$) (Table 6). This lack of positive and

We used a GGE Biplot to visualize mega-environments depending on lettuce performance across environments. A mega-environment is defined as the environment or environments in which germplasms perform statistically the same and the interaction with the environment is minimum. In the GGE Biplot, mega-environments are visualized with the which-won-where method graphed in a polygon to identify the germplasm(s) suitable for a specific mega-environment (one environment or the combination of several), which informs breeders of the location(s) on which selections should be carried out. As a result, we

Expt.	Expt. 1 (sand 2017)	Expt. 2 (sand 2018)	Expt. 3 (muck 2018)	Expt. 4 (muck 2019)
Expt. 1 (sand 2017)	—	0.26 (0.0292)	0.21 (0.0752)	0.29 (0.0128)
Expt. 2 (sand 2018)		—	−0.13 (0.2582)	−0.13 (0.3030)
Expt. 3 (muck 2018)			—	0.23 (0.0562)
Expt. 4 (muck 2019)				—

displayed the data of HW in a GGE biplot that helps to understand the $G \times S$ interaction in a graphic fashion (Yan, 2001). In a Biplot graphed by type of lettuce regardless of individual accessions, romaine lettuce had better and more stable HW in three of the environments tested Expts. 1, 2, and 3 (Sandy 2018, Sandy 2018, and Muck 2019) that were grouped as mega-environment 1, whereas iceberg lettuce was better in E4 (Muck 2019) in mega-environment 2 (Fig. 6A).

Biplot for HW are also presented for genotypes grouped in three lettuce types, butterhead, iceberg, and romaine lettuces, in Fig. 6B–D, respectively. The GGE Biplot divided the 4 experiments in two mega-environments: Expt. 1 (Sandy 2017) as one mega-environment and the other three Expts. 2, 3, and 4 (Sandy 2018, Muck 2018, and Muck 2019) in a second mega-environment for HW in butterhead lettuce. Interestingly, one breeding line (60176) and one obsolete cultivar (Floribibb) are positioned as the “winners” in mega-environment Expt. 1. Cultivar Palmetto is the winner in the second mega-environment and does well in three of the four experiments in this research, which is not surprising as the cultivar has been extensively used by growers in south Florida (Fig. 6B). In this research, a small group of butterhead lettuces were tested and most likely using a higher group of lines and cultivars may allow the identification of better suited butterhead lettuce cultivars for sandy soils.

In iceberg lettuce, two mega-environments were identified for all lettuce cultivars and breeding lines planted in four experiments. In mega-environment 1, Expts. 1 and 2 (Sandy 2017 and 2018) were grouped together on the unfavorable side (negative x and y axes) of the polygon. In mega-environment 2, Expts. 3 and 4 (Muck 2018 and 2019) were grouped together in a fair side of the polygon. However, only Expt. 3 falls into the productive side of the polygon (positive x and y axes), indicating the value of this group of icebergs for muck soils but not for sandy soils, in agreement with results previously described in this study (Fig. 6C). In mega-environment 2, ‘Chosen’ was the winner, a lettuce cultivar preferentially planted in the EAA during the early lettuce season (Sandoya and Lu, 2020).

In romaine lettuce, three mega-environments were identified as Expt. 1 (Sand 2017), Expts. 2 and 3 (Sand 2018 and Muck 2018), and Expt. 4 (Muck 2019). Interestingly, no romaine line or cultivar is graphed as the winner in Expt. 1. In the second mega-environment, cultivars Terrapin and Sawgrass, and breeding line 60182 were the winners, even though part of the mega-environment was graphed into the positive x and the negative y of the cartesian plane (Fig. 6D). The GGE biplot proved that romaine lettuce has good yield potential in sandy soils, as previously described and breeding lettuce cultivars adapted to sandy soils, especially romaine, should be conducted in sandy soil environments.

Adaptability of romaine accessions to early season planting in sandy soils. Three

romaine breeding lines and one obsolete cultivar were planted near the northern Florida town of Hastings to test the performance of romaine lettuce planted in sandy soil, ≈ 1 month before the current lettuce season in South Florida. Transplanting seedlings were initially grown in two locations, one in Blairsville, GA, and one in Sun City, FL. During the 3 weeks before transplanting, the Georgia location had an average temperature of 24 and 23 °C, respectively, in the first planting on 15 Aug. 2019 and in the second planting on 26 Aug. 2019, whereas the first and second plantings in Florida both had an average temperature of 27 °C. Although the maximum temperatures in both locations during those 3 weeks did not vary appreciably (between 30 and 33 °C), the variation between minimum temperatures was more pronounced (between 15 to 23 °C) (Table 4). On average, temperatures ranged from 24 to 26 °C while romaine lettuce was in the ground for the first transplanted experiment (Expt. 5) and ranged from 17 to 24 °C while romaine lettuce was in the ground for the second transplanted experiment (Expt. 6) in

northern Florida (Table 4). We found significant differences between the two planting times (15 Aug. 2019 and 26 Aug. 2019; $P = 0.0025$), among romaine accessions ($P = 0.0019$) and between locations where seedlings were initiated (Florida and Georgia; $P < 0.0001$) based on final HW measurements. There were also several significant interactions in the ANOVA ($P < 0.05$) such as genotype $\times$ planting and location $\times$ planting (Table 7).

Overall, romaine lettuce had a higher HW when transplants were initiated at the Georgia location in both experiments (Fig. 7), probably due to lower night temperatures (Table 4). Most lettuce performs best in cool weather where day temperatures range between 18 and 25 °C and night temperatures 10 and 15 °C, whereas higher temperatures negatively affect lettuce yields through reduced plant initiation and early flowering time (Cantliffe et al., 1981; Lafta and Mou, 2013). In this study, the minimum temperature in Aug. 2019 was 17 °C in Georgia and 23 °C in Florida (Table 4). As a result of this 6 °C difference, it is likely that the above

Table 7. Analysis of variance of head weight and bolting of four romaine accessions planted in two experiments in sandy soils near Hastings, FL. Seedlings for these experiments were started at two geographic locations in Georgia (Blairsville) and Florida (Sun City).

Source of variation	df _{num} ^z	df _{den} ^z	Head weight		Bolting	
			F value	P value	F value	P value
Genotype	3	28	6.39	0.0019	5.08	0.0062
Nursery	1	28	29.37	<0.0001	44.83	<0.0001
Genotype $\times$ nursery	3	28	0.50	0.6858	1.18	0.3364
Experiment	1	4	45.53	0.0025	60.50	0.0015
Genotype $\times$ experiment	3	28	4.26	0.0135	2.62	0.0701
Nursery $\times$ experiment	1	28	5.72	0.0237	19.36	0.0001
Genotype $\times$ nursery $\times$ experiment	3	28	1.07	0.3757	0.65	0.5899

^zdf_{num} is the degree of freedom of numerator, and df_{den} is the degree of freedom of denominator.

Fig. 7. Least square means (LSM) of head weight of three romaine breeding lines and one cultivar planted in nurseries in Georgia and Florida and transplanted in Hastings, FL. Error bars correspond with the SE of the LSM. Least significance difference (LSD; $P = 0.05$) is presented for cultivar/line (LSD = 67.6), nursery (LSD = 47.8), and cultivar/line $\times$ nursery (LSD = 95.6) interaction.

optimal minimum temperatures in Florida caused the lettuce to bolt faster and reduce time spent in vegetative growth (Table 8). These results suggest that the Georgia location is an ideal nursery for early planting when considering planting romaine lettuce in sandy soils, as supported by the higher bolting incidence among seedlings started in Florida (Table 8).

Considering differences in HW among genotypes across the two planting dates, the romaine breeding line BG18-0588 had the highest average HW followed by lines 60182, 70096, and cultivar Terrapin for both nurser-

ies (Fig. 7). Moreover, the yield of BG18-0588 remained consistent in both planting dates when transplants were obtained from Georgia, while the transplants from Florida performed significantly worse. The HW of 60182, 70096, and Terrapin were more negatively impacted by the first planting date regardless of transplant location (Fig. 8). These three genotypes did yield higher in the second experiment, especially among the Georgia transplants, suggesting that more genotypes may be suitable for a more modest, but still early, planting.

Table 8. Least square means of percentage of bolted plants in three romaine breeding lines and one cultivar planted in nurseries in Georgia and Florida (15 Aug. 2019 and 26 Aug. 2019) and transplanted in Hastings, FL.

Cultivar/Line	Planting 15 Aug.		Planting 26 Aug.	
	Georgia	Florida	Georgia	Florida
60182	35	97	0	0
70096	48	100	0	8
BG18-0588	7	68	0	0
Terrapin	33	100	0	50
Average	31	91	0	14
LSD (G) ^z	15.7			
LSD (P) ^y	18.8			
LSD (N) ^x	11.1			
LSD (G×P) ^w	23.1			
LSD (G×N) ^v	22.3			
LSD (N×P) ^u	17.1			
LSD (G×N×P) ^t	32.1			

^zLeast significant difference (LSD; $P = 0.05$) for genotype (G).

^yLSD ($P = 0.05$) for planting (P).

^xLSD ($P = 0.05$) for nursery (N).

^wLSD ($P = 0.05$) for genotype × planting (G×P).

^vLSD ($P = 0.05$) for genotype × nursery (G×N).

^uLSD ($P = 0.05$) for nursery × planting (N×P).

^tLSD ($P = 0.05$) for genotype × nursery × planting (G×N×P).

Fig. 8. Least square means (LSM) of head weight of three romaine breeding lines and one cultivar planted in nurseries in Georgia and Florida (15 Aug. 2019 and 16 Aug. 2019) and transplanted in Hastings, FL. Error bars correspond with the standard error of the LSM. Least significance difference (LSD; $P = 0.05$) is presented for cultivar/line (LSD = 67.6), nursery (LSD = 47.8), planting date (LSD = 84.4), and the interactions of cultivar/line × nursery (LSD = 95.6), cultivar/line × planting date (LSD = 100.2), nursery × planting date (LSD = 74.9), and cultivar/line × planting date × nursery (LSD = 138.3).

During the early season trials, bolting was highest in the first experiment when transplants originated from Florida, with an average bolting of 91%. Such a high percentage even prevented measuring HW data for '70096' and 'Terrapin'. On the other hand, Georgia's transplants in the first experiment registered an average of 31% of bolted plants, indicating that attempting to transplant at such an early date may not be possible for many genotypes. The second planting registered less bolting from Florida transplants (14%), which only occurred for line 70096 (8%) and cultivar Terrapin (50%), and no Georgia transplants bolted among any of the tested romaine breeding lines and cultivar (Table 8). This demonstrates that Georgia has greater potential as an early transplant nursery; however, specific bolting data should be generated for each cultivar to determine the best nursery location for transplants, especially when pushing lettuce planting to its earliest possible dates in Florida.

These observations indicate that certain genotypes, such as BG18-0588, might be less affected by warmer temperatures during very early plantings and further investigation is warranted to identify superior lines for early production in Florida's sandy soils. Results from breeding lines 60182 and 70096 show that although some lines may not be recommended for very early planting, even when using a cooler environment for seedling initiation, they are still a viable option for planting during slightly later dates that are still relatively early compared with the EAA season. This is evident by the fact that in E6, breeding line 60182 showed an almost identical HW between the two nursery locations (Fig. 8). Although HW was higher for 70096 and BG18-0588 when transplants were initiated in Georgia, these differences were not significant compared with the HW obtained using transplants from Florida (Fig. 8). Overall, this data warrants the screening of more romaine cultivars for adaptability to transplant nursery locations, acceptable HW, low tipburn, and little to no bolting when planted at moderately early dates in North Florida.

Comparing results across all four sandy experiments in Loxahatchee and Hastings, FL. Three romaine accessions (60182, 70096, and 'Terrapin') tested in both sandy soil locations presented a higher average yield when grown in Loxahatchee compared with Hastings, FL (Figs. 5–8), which may be explained by differences in fertilization and crop management strategies applied in each location. In addition, the Hastings experiments were conducted about one month before the beginning of South Florida's lettuce season, and therefore, warmer temperatures may have affected the yield and quality of lettuce plants (Lafta et al., 2017). Another contributing factor is that these three accessions were bred for cultivation in South Florida and may be adapted to shorter photoperiods. Future experiments could investigate whether improving fertilizer regimens could offset these latter two environmental conditions, or whether genotypes could be

identified that are less detrimentally impacted by these conditions.

Conclusions

In this research, genetic differences for HW and other heat-related stresses such as bolting and tipburn were observed among the breeding lines and cultivars tested in muck and sandy soils and these differences were most notable in romaine and butterhead lettuce; in addition, iceberg lettuce was not suitable for sandy soils. Overall, HW was better in sandy soil experiments in romaine cultivar Terrapin and breeding line 70096, which had no interactions between muck and sandy soils, whereas breeding line 60182 had an equivalent HW in both soils. The significant G×E interaction indicated that romaine lettuce is more suited for sandy soils based on HW, and therefore, breeding romaine lettuce for sandy soils should be conducted in sandy environments, as seen in the GGE Biplot. If selection is targeted, evaluations for HW and related traits should be conducted in several trials and locations as G×E seems to be a crossover type; further testing in several sand locations and the increase of accessions could help to understand the G×E interaction.

This research demonstrates that planting romaine lettuce in sandy soils could be beneficial to Florida growers. This lettuce type has become popular among leafy vegetable consumers in the United States. Romaine lettuce represents 35% of the total area planted in the country (USDA NASS, 2019). This trend in increased romaine preference has been occurring ever since this type of lettuce became one of the top 10 most consumed vegetables in the United States (Hayes, 2018), and producers could improve profits by meeting future demand increases through expanding their production into marginalized sandy soils. The crop could also have the potential to become a new, earlier planted crop in the sandy soils of northern Florida. If early planting becomes a reality in Florida, these results suggest that lettuce producers will need cooler nursery environments to produce seedlings, such as the Georgia location used in this study, with minimum temperatures below 18 °C. Using nurseries with higher temperatures during both early and late seasons, such as the nursery in Sun City, FL, would be more restricted to particularly heat-tolerant cultivars, such as the only heat-tolerant lettuce found in this research, BG18-0588.

Additionally, detrimental warm August temperatures could be avoided in northern Florida by adjusting the planting window by as little as 10 d, depending on yearly conditions, which still places a significant advantage over the necessarily later planting dates required in the warmer EAA. As a result, these early plantings would not interfere with the timing of the current Florida lettuce industry in the EAA because the asynchronous harvest dates would not compete for the same markets simultaneously. Lastly, additional beneficial practices, such as bed

mulching, fertigation, and transplanting required for producing lettuce in sand, may increase lettuce profitability through improved weed control and nutrient timing. Therefore, the results found in this study justify further economic analysis to investigate the feasibility of expanding Florida's current lettuce industry into sandy soils.

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