Planting date and in-row plant spacing effects on growth and yield of cabbage under plastic mulch

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Abstract: Florida is ranked third in total cabbage production in the U.S. and it is traditionally grown on bare ground with subirrigation. The use of plastic mulch and drip irrigation is widespread for other vegetable crops and can enhance water and fertilizer use efficiency and yield. The objective of the study was to evaluate plant growth, yield and head quality traits of cabbage using three plant populations and four planting dates on a plastic mulch system. Cabbage was transplanted in mid September (SEP), mid October (OCT), early November (NOV), and early December (DEC) in the 2013-14 and 2014-15 growing seasons, spanning the entire planting season for commercial operations in northeast Florida. There was no interaction among planting dates and plant populations for total and marketable yields or biomass. For both seasons, the SEP and OCT plantings showed a faster growth rate than NOV and DEC during the first 70 days after transplanting; however, differences in total biomass accumulation were only

seen in 2013-14. Biomass decreased quadratically in 2013-14 with an increase in in-row spacing. Average marketable yield for both years was 62.7, 60.5, 46.2, and 58.6 Mg ha⁻¹ for SEP, OCT, NOV and DEC, respectively. As plant population decreased, marketable yield increased linearly in 2013-14 while no differences were seen in marketable yield among plant population treatments during 2014-15 season. Plant growth rate and yield were correlated to growing season average air temperature and solar radiation. The SEP, OCT and DEC planting dates benefited from more favorable weather conditions, while low air temperatures and reduced solar radiation had a negative effect on cabbage yield for the NOV planting.

Key-words: Plastic mulch; Drip irrigation; Plant population; Fertigation; *Brassica oleracea* var. capitata

1. Introduction

Cabbage (*Brassica oleracea* var. capitata) production in Florida is traditionally grown on bareground with subirrigation. Subirrigation relies on large amounts of water to raise the water table for the purpose of irrigating crops. The shallow water table and the sandy soils commonly found in Florida favor this type of production system. However, the non-uniform distribution of soil moisture across fields and the offsite movement of soluble nutrients during large rainfall events increase the potential for reductions in crop yield. Growers have estimated that about 30% of the potential production under subirrigation does not reach marketable size and or quality.

Although in some vegetable production regions of south Florida the use of plastic mulch is combined with subirrigation, the use of drip irrigation instead of subirrigation can drastically reduce water use. Drip irrigation applies frequent, small volumes of water to the root zone, thereby enhancing soil moisture distribution and irrigation water use efficiency. The benefits provided by plastic mulch are the maintenance of soil moisture in the raised bed, potential reduction in nutrient leaching (Romic *et al.*, 2003), decrease in weed competition (Lament, 1993), and potential increase in plant population per area for some crops (Barrett *et al.*, 2015). Plastic mulch and drip irrigation has been successfully used in several horticultural crops and significant increases in marketable yield have been observed for eggplant, muskmelon, peppers, cucumbers, summer squash (Locascio, 2005), okra (Tiwari *et al.*, 1998), watermelons, tomato (Shrivastava *et al.*, 1994), bell pepper (Borosic *et al.*, 1998), and sweet potato (Laurie *et al.*, 2015) grown with a plasticulture system. The use of plastic mulch and drip irrigation in cabbage production resulted in a 70% yield increase when compared to a traditional furrow irrigation system (Tiwari *et al.*, 2003). In addition, the use of drip irrigation as an alternative to furrow irrigation, can reduce the incidence of soil pathogens (Xie *et al.*, 1999) and facilitate nutrient management.

In Northeast Florida, cabbage is commonly planted between the months of September and January, which exposes the crop to a wide range of weather conditions from plant establishment through harvest. Air temperature and solar radiation are key factors for cabbage growth and yield. Cabbage thrives best under cool weather conditions (Peirce, 1987; Swiader *et al.*, 1992). The air temperature range for optimum plant development is between 16°C (Criddle *et al.* 1997) and 20°C (Hara and Sonoda, 1982). Air

temperatures above and below this point tend to slow the rate of growth. In addition, cabbage head development is influenced by the availability of sunlight, especially during the early growth and head formation stages. Plant growth was increased during a growing season with higher levels of solar radiation (de Moel and Everaarts, 1990). While a reduction in solar radiation availability by 66% significantly reduced cabbage yields (Hara *et al.*, 1981; Hara and Sonoda, 1981).

Staggering crop planting dates is a strategy commonly used by vegetable growers to maintain a continuous supply of fresh product. Staggering planting dates may also reduce economic risk by avoiding yield losses due to undesirable environmental conditions and by targeting high market price windows. Previous studies of cabbage grown on bare ground in northern states found that planting date significantly impacted marketable yield (de Moel and Everaarts, 1990; Kleinhenz and Wszelaki, 2003; Orzolek *et al.*, 2000; Sundstrom and Story, 1984; Wszelaki and Kleinhenz, 2003). However, no previous research has investigated the use of plasticulture throughout the entire range of cabbage planting dates for subtropical latitudes, or evaluated production as correlated to the corresponding environmental conditions.

The use of a high plant population is a strategy to increase yield per area and has been used in other brassicas such as broccoli (*Brassica oleracea* var. *italica*) and cauliflower (*Brassica oleracea* var. *botrytis*) (Dixon, 2006). Low cabbage marketable yields caused by a reduction in average head size when using high plant populations can be minimized by extending the growth period (de Moel and Everaarts, 1990) and through a reduction in competition for light and nutrients. However, extending the growing period is not always an option for Florida because of the variability in weather conditions such

as high air temperatures and excessive rainfall which can compromise cabbage quality. Halsey *et al.* (1966) suggested that marketable cabbage yield was higher under Florida conditions when in-row plant spacing was increased from 23 to 30 cm for bare ground production. Barrett *et al.* (2015) evaluated plant population treatments of cabbage under plastic mulch using different arrangements of in-row plant spacing and number of rows per bed. The study showed that marketable yield was maximized using three or four rows of cabbage per 1.2 m bed with in-row spacings between 25 and 35 cm. The objectives of this study were to evaluate cabbage plant growth, yield and head quality traits from four planting dates with high plant populations using a plastic mulch and drip irrigation system. This research intends to provide information for making management decisions with regard to plant population and planting dates for cabbage production in subtropical environment.

2. Material and Methods

Field experiments were carried out at the University of Florida, Hastings Agricultural Extension Center in Hastings, FL (29.69 N; -81.44 W) during the 2013-14 and 2014-15 growing seasons. The soil is characterized as a Placid fine sand: sandy, siliceous, hyperthermic, typic, humaquepts (Readle, 1983). Four rows of cabbage was grown on 1.2 m wide raised beds and the distance between bed centers was 2 m (Barrett *et al.*, 2015). Beds were covered with black plastic mulch (1.8 m width, 1.25 mm thickness, VIF film, Polygro, LLC. Safety Harbor, FL) and two drip tapes spaced 0.6m apart (Aqua-Traxx model EA5081222, 16 mm diameter, 0.3 m emitter spacing, emitter flow of 0.5 L h⁻¹ at 55 kPa, Toro Agricultural Irrigation, El Cajon, CA).

112 A granular fertilizer mix of 10N-4.3P-8.3K was incorporated into beds at a rate of 168
113 kg•ha⁻¹ of P₂O₅ prior to fumigation. Beds were fumigated (39% dichloropropene, 59.6%
114 chloropicrin) at a rate of 148 kg ha⁻¹ prior to drip tape and plastic mulch placement. Pre-
115 plant fertilizer supplied 42%, 100%, and 42% of the total N, P, and K respectively. A
116 total of 157 kg•ha⁻¹ of N and K₂O were applied in a split application by fertigation
117 through the surface drip tape. The materials used for fertigation were calcium nitrate
118 (15.5N-0P-0K) and muriate potash (0N-0P-50K). There were four fertigation events, one
119 every two weeks starting at two weeks after transplanting. The proportion of N and K₂O
120 applied in each fertigation event was equivalent to 8%, 15%, 20%, and 15% of the total
121 N and K₂O applied to match the growth of the crop.

122 The treatments were arranged in a split plot design with randomized complete blocks
123 and four replications. Four planting dates were assigned as the main plot factor.
124 Cabbage cv. Bravo was transplanted on 17 September (SEP), 11 October (OCT), 7
125 November (NOV), and 3 December (DEC) of 2013 for the 2013-14 growing season and
126 16 September, 9 October, 4 November, and 2 December of 2014 for the 2014-15
127 growing season. Three plant populations were assigned as the sub-plot factor. The in-
128 row plant spacings used were 25, 30, and 35 cm, resulting in plant populations of
129 77,500, 64,583, and 55,357 plants•ha⁻¹, respectively. Main plots were 31.8 m long and
130 sub-plots were 10.6 m long. A tractor-mounted hole puncher was used to make four
131 rows of holes, 0.3 m apart on the raised beds.

132 *Biomass:* To assess plant growth, two representative plants per treatment were
133 harvested biweekly from transplanting to harvest. The plants were collected from one

internal and one external row of the raised beds. Samples were dried at 65° C until stable weight for subsequent mass measurement.

Yield: The center six meters of each plot were harvested for yield and head trait data. The first harvest occurred when approximately 50% of the cabbage heads reached 1 kg, while all remaining plants were harvested during a second harvest. Cabbage was harvested by cutting the stem at the soil surface. The heads were weighed before and after the removal of the outer wrapper leaves. Cabbage heads were classified as marketable when trimmed head weight was above 1 kg and unmarketable for head weight below 1 kg. Total cabbage yield was calculated as marketable and unmarketable trimmed heads. A total of 20 cabbage heads (5 per heads per row) per plot were randomly selected for internal quality evaluation. Measurements of cabbage head equatorial and polar diameter, core length, and core base width were recorded. Cabbage heads were treated as a sphere for the head volume calculation and cores were treated as a cone for the volume calculation, as described by Kleinhenz and Wszelaki (2003). During the 2014-15 season, an overhead irrigation system was utilized to improve plant establishment. The weather station number 270 from Florida Automated Weather Network (www.fawn.ifas.ufl.edu) located within 100 m of the experimental site provided air temperature, relative humidity, solar radiation, and wind speed data every 15 minutes. Growing degree days were calculated by averaging daily maximum and minimum air temperature minus the base temperature of 10° C (Isenberg *et al.*, 1975).

Data Analysis: An analysis of variance (ANOVA) for each measured variable was conducted for both growing seasons using the GLIMMIX procedure in SAS Version 9.4

(SAS Institute, Cary, NC). A combined ANOVA using both seasons resulted in significant interaction between planting dates and seasons for all measured parameters, therefore individual ANOVAs were performed for each growing season. Plant biomass was analyzed independently at each measured crop stage. When the F-value was significant for planting date treatment, a multiple comparison was performed using the Tukey-Kramer test with $P \leq 0.05$. Regression analysis was used to verify linear or quadratic responses for in-row plant spacing treatments and cabbage marketable yield response to the average air temperature of each planting date. A matrix of Pearson correlations (r) was used to identify weather parameters that were significantly correlated with yield. To control for the high degree of multicollinearity between the weather variables, regression analyses were completed with variables that had a significant correlation and variance inflation factors were calculated to check for collinearity in the model. Pearson correlations and regression analyses were completed using the CORR and REG procedures in SAS Version 9.4. Biomass accumulation logistic curves were fitted by adapting the equation presented by (Witty, 1983) as follows: crop above ground biomass accumulation = $M / [1 + e^{-K(t-l)}]$. In this formula, “M” is maximum crop dry biomass, “K” is crop biomass accumulation rate constant, “t” is time in days, and “l” is days to half maximum biomass accumulation.

3. Results

3.1 Weather Conditions

Air temperature and solar radiation were major factors affecting cabbage growth, maturation, and yield across the four planting dates. The number of days to reach maturity increased from the SEP through DEC planting dates. For both seasons, the first harvest occurred at 88 ± 6 , 94 ± 3 , 97 ± 1 , and 102 ± 4 days after transplanting ($\pm$

standard deviation) for SEP, OCT, NOV, and DEC plantings, respectively. However, for both seasons, the total length of the growing season from planting until final harvest was similar for SEP, NOV, and DEC with an average of 114 ± 4 days and 123 ± 1 days for the OCT planting date.

The 2013-14 growing season averaged 0.9°C warmer than 2014-15 during SEP, OCT, and NOV and 0.6°C warmer for DEC. The average air temperature over the entire growing season for both years were 19.1 , 16.0 , 15.1 and 15.3°C for SEP, OCT, NOV, and DEC planting dates, respectively. Different trends of air temperature were observed among planting dates. The SEP and OCT plantings were characterized by high air temperatures during the beginning of the plant growing cycle with an overall decrease in air temperature as the season progressed (Fig. 1). Conversely, the NOV and DEC plantings seasons started with low air temperatures to a point and then an increase in air temperature was observed until final harvest (Fig. 1).

Solar radiation varied as function of photoperiod and atmospheric conditions, such as rain and cloud cover. For example, September had a daily average photoperiod of 12.1 h, while January and March had 10.1 and 11.8 h, respectively. Staggered planting treatments resulted in differences in total accumulation of solar radiation throughout the growing cycle. An overall 6% increase in solar radiation was observed among planting dates in 2014-15 compared to 2013-14 season. The SEP and OCT plantings were characterized by higher solar radiation during the first half of the growing cycle, while the NOV planting treatment coincided with lower solar radiation and lower air temperatures during most of the crop cycle. Conversely, the DEC planting received higher solar radiation during the second half of the growing cycle compared to the other

planting dates (Fig. 1), which resulted in similar solar radiation accumulation between the SEP (1305 MJ m⁻² d⁻¹) and DEC (1370 MJ m⁻² d⁻¹) planting dates. The SEP and DEC planting dates accumulated 7% and 16% more solar radiation compared to OCT and 14% and 22% more than NOV during 2013-14 season. In 2014-15, the SEP, OCT, and DEC plantings had similar accumulation of solar radiation which was about 10% higher than NOV planting.

3.2 Biomass

The SEP planting date resulted in higher overall biomass accumulation rate compared to the other planting dates (Fig. 2). The crop biomass accumulation rate constant (K) ranked as follow: SEP > OCT > NOV = DEC. The time required to reach half of the maximum biomass according to the logistic models, averaged 60 days for the SEP planting compared to 70, 73, and 78 days for OCT, NOV and DEC, respectively. There was no interaction between planting dates and in-row plant spacing for total biomass accumulation at the final harvest. Differences in total biomass accumulation among planting dates were only seen in 2013-14 (Table 1). During that year, the OCT and NOV plantings produced 9.40 and 9.10 Mg ha⁻¹ of dry biomass, respectively, which were 14% and 11% higher than the 8.10 Mg ha⁻¹ for the DEC planting. A quadratic decrease in biomass accumulation was observed as the in-row plant spacing increased in 2013-14. The 25 cm in-row spacing produced 9% more biomass than the 35 cm in-row spacing, which averaged 9.42 Mg ha⁻¹. There was no significant difference in biomass accumulation among planting dates or in-row spacing in 2014-15 (Table 1).

3.3 Total Yield

There was no interaction among planting dates and in-row plant spacing treatments for total yield within each growing season. In 2013-14, the OCT planting date had the highest total yield with 74.0 Mg ha⁻¹, representing 9%, 15%, and 47% more yield than the SEP, NOV, and DEC planting dates, respectively. For 2014-15 season, the SEP and DEC plantings achieved the highest total cabbage yield, averaging 78.1 and 75.6 Mg ha⁻¹, which represented 16% and 13% higher yield than OCT, respectively, and 34% and 30% higher yield than NOV planting date, respectively (Table 1). For both seasons, total yield did not differ among in-row plant spacing treatments.

3.4 Marketable Yield

The ratio of marketable to total yield was similar in both growing seasons. Marketable yield accounted for 86% and 83% of the total cabbage yield harvested in the 2013-14 and 2014-15 seasons, respectively.

There was no interaction among planting dates and in-row plant spacing treatments for cabbage marketable yield in both seasons. Among planting dates, the highest percentage of marketable yields (ratio marketable:total yield) was achieved in DEC, with 93% in both seasons. The SEP, OCT, and NOV planting dates averaged 86%, 82%, and 75% marketable yields, respectively. In 2013-14, the OCT planting produced a significantly higher marketable yield than SEP, NOV, and DEC with 64.9 Mg ha⁻¹ (Table 1). In 2014-15, the SEP and DEC planting dates produced 68.6 and 70.4 Mg ha⁻¹, respectively, and were significantly higher compared with the OCT and NOV planting dates. Marketable yield increased linearly as in-row spacing increased in 2013-14. The 35 cm in-row spacing treatment produced 58.9 Mg ha⁻¹, which represented 14% and 8%

more than 25 and 30 cm in-row spacing treatments. Conversely, marketable yield did not differ among in-row plant spacing treatments during 2014-15 season (Table 1).

3.5 Marketable Head Weight

The marketable head weight ranged from 1.21 to 1.49 kg head⁻¹ (Table 1). In 2013-14 the DEC planting resulted in a significantly higher marketable head weight compared to the other treatments, with 1.49 kg head⁻¹. In 2014-15 season, the marketable head weight was similar among planting dates with an average of 1.34 kg head⁻¹, except for the NOV planting, which was 10% lower with 1.21 kg head⁻¹. For both seasons, there was a quadratic increase in marketable head weight as in-row spacing increased (Table 1).

3.6 Number of Heads

The overall number of marketable heads harvested in the 2013-14 season was 14% lower than the 2014-15 season. Similar to the total number of heads, the DEC planting also had the lowest number of marketable heads harvested in the 2013-14 season, associated with the highest absolute number of heads under 1 kg (unmarketable). There was an increase in the number of unmarketable heads from the SEP through DEC planting dates in 2013-14 (Table 2).

There was a significant interaction between planting date and in-row plant spacing for marketable and small heads in the 2014-15 season (Table 3). Within the SEP and DEC plantings, all in-row plant spacing treatments had a similar quantity of marketable heads. Conversely, within the OCT planting, a quadratic response was observed for the number of marketable heads among in-row spacing treatments. The 30 cm in-row

spacing resulted in the highest number of marketable heads with 45,400 heads ha⁻¹. For the NOV planting, there was also a quadratic increase in the number of marketable heads with an increase in-row plant spacing. The 35 cm in-row spacing had 38,900 marketable heads, which represented 32% and 6% more than 25 and 30 cm in-row spacing, respectively (Table 3). Regardless of the in-row plant spacing, the SEP and DEC plantings produced more marketable heads than the OCT and NOV planting dates.

For all planting dates in 2014-15, the number of small heads decreased quadratically as in-row spacing increased. The SEP, OCT, and NOV plantings averaged 45% and 69% fewer small heads for 30 and 35 cm, respectively, compared to 25 cm in-row spacing. Within the DEC planting, the 25 cm in-row spacing produced 20,300 small heads, which represented 75% and 95% more than 30 and 35 cm, respectively (Table 3).

3.7 Head Traits

Planting date significantly affected head equatorial and polar diameters (Table 4). Head equatorial diameter for the OCT planting was 14.7 cm, which was significantly larger than the SEP and NOV plantings, but not different from DEC in 2013-14. In 2014-15, the SEP and DEC plantings produced heads with significantly larger equatorial diameters than the OCT and NOV plantings. No differences were seen among in-row plant spacing for either season. The NOV planting date produced consistently smaller head polar diameters in both seasons compared to the other planting dates (Table 4). A linear and quadratic response in head polar diameter was observed as in-row spacing increased for 2013-14 and 2014-15, respectively.

There were significant differences in core volume among planting dates in 2013-14. The SEP planting date had a greater core volume than the NOV and DEC plantings with 19.1 cm³ (Table 4). In-row plant spacing did not show a significant effect on core volume or head density for either season. A consistent decrease in cabbage head density was observed from SEP to DEC planting dates in both 2013-14 and 2014-15. Head density decreased by 15% from SEP to DEC (Table 4).

4. Discussion

The ability of cabbage plants to reach maturity was directly related to the success of transplant establishment and weather conditions. Since cabbage grows best under cool air temperatures (Peirce, 1987; Swiader *et al.*, 1992), the predominantly elevated air temperatures during the SEP and OCT plantings made transplant establishment more difficult. Roots were confined in the transplant plugs with limited access to water right after transplant. In addition, the surface temperature of the black plastic mulch was generally higher than the air temperature during the hotter times of the day. In SEP and OCT, the transplants that touched the plastic incurred some leaf damage related to heat stress. During the 2014-15 season for all planting dates, an overhead sprinkler irrigation system was used during the first 10 days after the cabbage was transplanted to improve plant establishment. The use of overhead irrigation likely contributed to the increase in the overall number of cabbage heads harvested in the 2014-15 season (Table 2). Overhead sprinkler irrigation on recent transplants is a common practice for cabbage cultivated on subirrigation because of the inability of the irrigation system to bring moisture to the transplants through raising the water table.

314 Variability in weather conditions between growing seasons and among planting dates
315 was observed during the two years of this experiment. This variation directly affected
316 plant growth and final productivity. An overall increase in total biomass accumulation
317 and total and marketable yields was observed from 2013-14 to 2014-15, respectively.
318 This may be attributed to a greater plant survival as well as more favorable weather
319 conditions during the 2014-15 season, such as cooler air temperatures and higher solar
320 radiation accumulation. Criddle *et al.* (1997) and Hara and Sonoda (1982) reported
321 optimum air temperatures for plant development and cabbage head formation of 16 °C
322 and 20 °C, respectively. In combination with ideal air temperature, higher solar radiation
323 availability will favor cabbage head development when adequate nitrogen is supplied
324 (Hara *et al.*, 1981). Similar outcomes with cabbage cv. Bravo yields due to seasonal
325 temperatures have been previously reported for bare ground production. During the
326 1992-93 and 1993-94 cabbage seasons in Manatee County, FL, Howe and Waters
327 (1994) reported an increase in yields from 46.9 Mg ha⁻¹ to 69.3 Mg ha⁻¹ when the
328 average air temperature decreased from 20 °C in the first season to 17.7 °C in the
329 second season. Barrett *et al.*, (2015) reported higher marketable yields for cabbage
330 grown in Hastings, FL under plasticulture for cabbage planted in early December 2010,
331 with an average air temperature of 13.5 °C compared to 16.3 °C and 16.1 °C for
332 planting dates in October and early December, respectively, the following year. Despite
333 the average air temperature being below the ideal range of 16-20° C, an extended
334 growth period likely exposed the crop to sufficient solar radiation, which promoted an
335 increase in the number of marketable heads and increased the marketable yields for the
336 2010-11 season.

337 There was a significant effect of planting dates on cabbage total and marketable yields,
 338 supporting previous findings (de Moel and Everaarts, 1990; Kleinhenz and Wszelaki,
 339 2003; Orzolek *et al.*, 2000; Sundstrom and Story, 1984; Wszelaki and Kleinhenz, 2003).
 340 However, none of these studies were conducted using plastic mulching. Differences in
 341 air temperature and solar radiation among the planting dates were the major
 342 environmental factors affecting cabbage plant performance. A significant correlation
 343 was obtained between marketable yield and mean air temperature during the crop
 344 season ($r = 0.40$, $P < 0.0001$). A quadratic relationship ($Y_{\text{marketable}} = -1109.173 + 134.464$
 345 $T_{\text{mean}} - 3.826 T_{\text{mean}}^2$, $r^2 = 0.59$, $P < 0.0001$) showed that marketable yields were
 346 maximized at an average air temperature of about 17.5 °C for the Hastings, FL area.
 347 There was no correlation between mean solar radiation and yield, when this parameter
 348 was evaluated by itself. However, the interactive effect of average air temperature and
 349 solar radiation combined resulted in a significant correlation with marketable yield, head
 350 weight and head density ($r = 0.38$; 0.23; 0.35, respectively, all at $P < 0.0001$). The
 351 quadratic response of marketable yield to the combined effect of average air
 352 temperature and average solar radiation (SR_{mean}) was described by the following
 353 equation ($Y_{\text{marketable}} = -343.953 - 0.01031 (T_{\text{mean}} * SR_{\text{mean}}) - 4.10489 (T_{\text{mean}} * SR_{\text{mean}})^2$, $r^2 =$
 354 0.26, $P < 0.0001$).
 355 The characteristics of high air temperature and solar radiation during the initial growing
 356 stages of the SEP planting promoted a more rapid increase in biomass accumulation
 357 (Fig. 2). De Moel and Everaarts (1990) also attributed an increase in biomass
 358 accumulation from two cabbage seasons to the increase in solar radiation intensity. The
 359 minimum air temperatures above 19 °C may have led to heat stress, which negatively

360 affected the development of cabbage heads and yield in 2013-14. The use of an
361 overhead irrigation system in 2014-15 during the establishment period attenuated the
362 heat stress during initial plant development. This may have contributed to the
363 enhancement of head development and the achievement of higher total and marketable
364 yields than the previous year. For the OCT planting in both years, air temperatures
365 averaged 2.6 °C cooler and solar radiation was lower during the first 70 days after
366 transplanting compared to SEP, resulting in a decrease in heat stress as well as
367 reduced plant growth rate. Moreover, compared to NOV and DEC, the OCT planting
368 had fewer days with an average air temperature below 16 °C in 2013-14 and 2014-15.
369 These conditions may have contributed to OCT having higher total and marketable
370 yields in 2013-14 than NOV and DEC plantings (Table 1). In addition, the longer
371 growing cycle for OCT, caused by reduced solar radiation and temperature during head
372 formation, allowed an increase in the number of heads reaching the marketable size
373 compared to other plantings. Conversely, during the 2014-15 season, the transplants
374 acquired for OCT were of poor quality (etiolated and weak transplants) and did not
375 display optimal cabbage head development. Thus, the number of marketable heads and
376 consequently the marketable yields, were reduced when compared to the previous
377 season. The NOV planting date experienced three freezing events during head
378 formation in 2013-14 and freezing events at plant establishment, head formation, and
379 late in the season during the 2014-15 season (Fig. 1). These conditions, combined with
380 the reduced solar radiation throughout entire growing season, slowed the plant growth
381 rate and prevented the cabbage heads from fully developing until harvest, resulting in
382 the lowest marketable yields. For the DEC planting, the lowest average air temperature

during initial growing stages promoted a slower plant growth. However, the increase in air temperature and solar radiation during the end of winter and onset of spring provided beneficial growing conditions for head development. These conditions likely contributed to the highest number of marketable heads (Table 3) as well as total and marketable yield in 2014-15 (Table 1). Additionally, the DEC planting had the largest marketable head weight in both seasons. Although similar weather conditions occurred during both seasons, a lower plant survival rate in 2013-14 led to the decrease in total and marketable yields.

The differences in yield among in-row plant spacing treatments were not correlated to the weather parameters and was confirmed by the lack of interaction between planting dates and in-row spacing treatments. Inter-plant competition at different in-row spacings was the major factor affecting biomass accumulation and yield. There was an increase in biomass accumulation as in-row spacing decreased only in 2013-14 (Table 1). The favorable weather conditions in 2014-15 described previously may have led to a greater growth of plants with wider in-row spacings. Therefore, this may have compensated for the reduced plant population in the 30 and 35 cm in-row spacings, resulting in similar biomass accumulation and marketable yield among all treatments. The higher total yield achieved at narrower in-row plant spacing (Table 1), followed the same pattern as described by Stoffella and Fleming (1990). Halsey *et al.* (1966) reported no differences in marketable yield at 23, 30, and 38 cm in-row plant spacing treatments. However, their studies were conducted on bare ground with one plant row per bed. In the present study, the high plant population with four rows per bed created higher inter-plant competition, and as the in-row plant spacing increased, the marketable yield increased

linearly in 2013-14. Although a narrower in-row plant spacing promoted an increase in plant population and therefore total yield, the greater inter-plant competition led to a decrease in head size and marketable yield.

Marketable cabbage head weight increased quadratically with an increase in in-row plant spacing. Similarly, Stoffella and Fleming (1990) reported a quadratic increase in cabbage head weight as the in-row plant spacing increased from 8 to 38 cm. Halsey *et al.* (1966) also observed a significant increase in head weight as the in-row plant spacing increased from 23 to 38 cm. As reported by Stoffella and Fleming (1990) and Barrett *et al.*, (2015), longer head polar diameter was observed for wider in-row plant spacing, suggesting that less inter-plant competition for sunlight and nutrients promoted greater head size. The decrease in head density from SEP to DEC in both seasons may be associated with low solar radiation during the early head formation period. The SEP, OCT, NOV and DEC plantings daily averaged in both seasons 13.2, 11.8, 9.4 and 9.9 MJ m⁻² d⁻¹ during the first 60 day of growing cycle. Low light intensity would decrease photosynthesis and the carbohydrate content in the leaves, which may have decreased head density. This is supported by the work of Hara *et al.* (1981), who reported that the inner leaves of cabbage heads were loosely folded and rigidity was decreased when grown at low light intensity.

In-row plant spacing did not affect core length or core width (data not shown) in either season. However, differences were seen in planting date treatments where core width decreased from SEP to DEC plantings and core length increased from the SEP to DEC plantings in both seasons. Sundstrom and Story (1984) also found greater core elongation for cabbage grown under cooler air temperatures and reduced solar radiation

in Louisiana. Conversely, Kleinhenz and Wszelaki (2003), reported no differences in core length and width for cabbage planted in May compared to a June-July planting date in Ohio. Given the different latitudes between Florida, Louisiana and Ohio, the conflicting results may be attributed to differences in day length and air temperatures.

5. Conclusions

Differences in total and marketable yields and head traits among the planting dates were influenced by an interactive effect of air temperature and solar radiation. An average air temperature of 17.5 °C combined with high solar radiation availability were ideal conditions for optimum cabbage head development. In this study, the SEP and OCT planting dates presented a more favorable average air temperature during the growing cycle, while the DEC planting date benefited most from an increase in solar radiation during head formation. The NOV planting date was the treatment most affected by adverse weather conditions. In this case, wider in-row spacing may be selected to decrease inter-plant competition to optimize the solar radiation absorption. The differences found for in-row plant spacing treatments were attributed to the effect of inter-plant competition. The 35 cm in-row spacing was the treatment that consistently produced greater marketable yields, and therefore may be selected to maximize productivity. However, if smaller heads become desirable in the market, narrower in-row spacing would be preferred.

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Table 1. Biomass accumulation, total and marketable yield, and marketable head weight of ‘Bravo’ cabbage at four planting dates and three plant spacings during the 2013-14 and 2014-15 growing seasons.

Planting date	Biomass accumulation ^{xy}		Total yield ^{xy}		Marketable yield ^{xy}		Mkt head weight ^{xy}	
	(Mg ha ⁻¹)		(Mg ha ⁻¹)		(Mg ha ⁻¹)		(kg head ⁻¹)	
	2013-14	2014-15	2013-14	2014-15	2013-14	2014-15	2013-14	2014-15
SEP	8.96 ab	10.07	67.8 b	78.1 a	56.8 b	68.6 a	1.34 c	1.36 a
OCT	9.40 a	9.41	74.0 a	67.0 b	64.9 a	56.1 b	1.42 b	1.32 a
NOV	9.10 a	9.44	64.1 b	58.2 c	50.2 c	42.1 c	1.29 c	1.21 b
DEC	8.10 b	9.34	50.1 c	75.6 a	46.9 c	70.4 a	1.49 a	1.35 a
Spacing (cm)								
25	9.42	9.97	65.9	71.0	50.9	54.1	1.32	1.27
30	8.68	9.55	63.8	70.8	54.2	61.5	1.39	1.28
35	8.58	9.18	62.4	67.3	58.9	62.3	1.45	1.39
	Q*	ns	ns	ns	L*	ns	Q*	Q**

^xMeans followed by the same lowercase letter within columns for planting date indicate no significant differences ($P \leq 0.05$). Mean separation by Tukey-Kramer test.

^yRegression analysis for the effect of in-row spacing: L, liner; Q, quadratic, * $P < 0.05$; ** $P < 0.01$; ns, not significant for L or Q.

Table 2. Number of total, marketable (>1kg), and small heads (<1kg) harvested for 'Bravo' cabbage at four planting dates and three plant spacings during the 2013-14 and 2014-15 growing seasons.

Planting date	Total heads x1000 ^{xy} (number/ha)		Mkt heads x 1000 ^{xy} (number/ha)		Small heads x 1000 ^{xy} (number/ha)	
	2013-14	2014-15	2013-14	2014-15	2013-14	2014-15
SEP	61.1 ab	65.8 a	42.4 ab	-	18.7 bc	-
OCT	60.9 ab	62.9 ab	45.7 a	-	15.2 c	-
NOV	62.7 a	63.9 ab	38.7 b	-	23.9 ab	-
DEC	56.2 b	61.4 b	29.1 c	-	27.1 a	-
Spacing (cm)						
25	69.2	73.2	38.1	-	31.1	-
30	59.4	63.8	39.1	-	20.3	-
35	52.1	53.1	39.8	-	12.3	-
	Q**	Q**	ns	*	Q**	*

^xMeans followed by the same lowercase letter within columns for planting date indicate no significant differences ($P \leq 0.05$). Mean separation by Tukey-Kramer test.

^yRegression analysis for the effect of in-row spacing: L, liner; Q, quadratic, * $P < 0.05$; ** $P < 0.01$; ns, not significant for L or Q.

Table 3. Interactive effects of planting date and plant spacing on number of marketable and small heads for 'Bravo' cabbage harvested during the 2014-15 growing season.

Spacing (cm)	Mkt heads (no./ha) x 1000 ^{xy}				Small heads (no./ha) x 1000 ^{xy}			
	SEP	OCT	NOV	DEC	SEP	OCT	NOV	DEC
25	48.6 A	41.3 B	26.4 C	51.8 A	25.8 BC	31.4 B	46.8 A	20.3 C
30	52.6 A	45.4 B	36.5 C	56.3 A	13.1 B	16.9 B	28.8 A	5.4 C
35	49.6 A	41.1 B	38.9 B	49.2 A	7.6 AB	10.4 A	14.1 A	1.0 B
	ns	Q*	Q**	ns	Q**	Q**	Q**	Q**

^xMeans followed by the same uppercase letter within the same in-row spacing indicate no significant differences ($P \leq 0.05$) among planting dates.

Mean separation by Tukey-Kramer test.

^yRegression analysis for the effect of in-row spacing: L, liner; Q, quadratic, * $P < 0.05$; ** $P < 0.01$; ns, not significant for L or Q.

Table 4. Head equatorial diameter, head polar diameter, core volume, and density of 'Bravo' cabbage heads grown at four different planting dates and three plant spacings.

Planting date	Head Equatorial ^{xy} (cm)		Head Polar ^{xy} (cm)		Core volume ^{xy} (cm ³)		Density ^{xy} (g*cm ³)	
	2013-14	2014-15	2013-14	2014-15	2013-14	2014-15	2013-14	2014-15
SEP	13.4 b	15.2 a	13.2 a	13.9 a	19.1 a	17.2	0.86 a	0.74 ab
OCT	14.7 a	14.2 b	13.5 a	13.4 b	17.9 ab	16.9	0.78 ab	0.77 a
NOV	13.8 b	13.9 b	12.4 b	12.9 c	15.8 b	16.3	0.73 bc	0.70 bc
DEC	14.2 ab	15.4 a	13.2 a	13.4 b	16.4 b	16.6	0.68 c	0.68 c
Spacing (cm)								
25	13.8	14.3	12.8	13.1	17.6	16.2	0.73	0.72
30	13.9	15.0	13.0	13.4	17.6	16.9	0.76	0.70
35	14.3	14.7	13.3	13.6	16.9	17.0	0.8	0.74
	ns	ns	L*	Q*	ns	ns	ns	ns

^xMeans followed by the same lowercase letter within columns for planting date indicate no significant differences ($P \leq 0.05$). Mean separation by Tukey-Kramer test.

^yRegression analysis for the effect of in-row spacing: L, liner; Q, quadratic, * $P < 0.05$; ** $P < 0.01$; ns, not significant for L or Q.

Figure 1. Maximum and minimum air temperatures (°C), daily solar radiation and cumulative growing degree days for all planting dates and throughout 2013-14 and 2014-15 cabbage seasons in Hastings-FL. Data source: Florida Automated Network (<<http://fawn.ifas.ufl.edu/>>)

Figure 2. Biomass accumulation (Mg ha⁻¹) for all planting dates throughout 2013-14 and 2014-15 cabbage season in Hastings, FL. Error bars represent standard error of the mean of biomass accumulation.