Determining Optimal Bulb Storage and Production Methods for Successful Forcing of Cut Pineapple Lily

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SUMMARY. Pineapple lily (*Eucomis* hybrids) has long, striking inflorescences that work well as a cut flower, but information is needed on proper production methods and postharvest handling protocols. The objective of this study was to determine the effects of bulb storage temperature and duration, production environment, planting density, and forcing temperatures on cut flower production of ‘Coral’, ‘Cream’, ‘Lavender’, and ‘Sparkling Burgundy’ pineapple lily. Stem length was greater in the greenhouse than the field and at the low planting density. Plants in the field at the low planting density had the shortest stem length for ‘Coral’ and ‘Cream’, but still produced marketable lengths of at least 30 cm. Planting density did not affect ‘Lavender’ and ‘Sparkling Burgundy’ stem length or number of marketable stems. The productivity (number of marketable stems per bulb) was affected only by planting density for ‘Coral’ and planting environment for ‘Cream’. Differences in stem quality and productivity differed for each cultivar and planting density over the next two seasons. The productivity of ‘Coral’ increased significantly from year to year, while the productivity of ‘Cream’ only significantly increased between the first and second years. The low planting density resulted in slightly more stems per bulb for ‘Coral’ over the next two seasons. Emergence after bulb storage treatments was highest in treatments where the bulbs were not lifted from the substrate and were subsequently grown at 18 °C. Bulbs grown in the warmest (18 °C) production temperature flowered soonest and had shorter stem lengths. For earliest flowering, bulbs should be stored in substrate in cool temperatures of at least 13 °C and forced at warm temperatures of at least 18 °C.

New cut flower introductions are necessary to maintain and increase consumer interest. Expanding the availability and knowledge of new cut flowers allows growers to select species and cultivars ideally suited for their climates and consumer base. Many exotic bulb species, such as pineapple lily, are underused by the floral industry. The genus *Eucomis* contains about 15 species (Bryan and Griffiths, 1995) and many hybridized cultivars now exist that vary in color, scent, vigor, and hardiness (Fig. 1). Pineapple lily grows from a true bulb forming a rosette of lanceolate leaves. From that rosette emerges a spike inflorescence composed of star-shaped florets and a terminal tuft of

bracts making it resemble a pineapple, from which its common name is derived. The inflorescence has the potential to last for more than a month in a vase with proper postharvest handling (Carlson and Dole, 2014) and even longer on the plant. New cultivars and species appear to have potential, but growers are hesitant to produce new cut flower crops without information on production techniques.

Plant material and production area are costly; therefore, it is important that optimum planting densities be identified to maximize financial return (Rees, 1974). Planting density can strongly affect the yield of bulb crops (de Vroomen, 1974), weed and disease control, and mechanization

(Rees, 1974). Increasing planting density to increase productivity per unit area can decrease the productivity per plant, increase stem length, and increase earliness of flowering depending on the species (Rees, 1974). Higher rates of transpiration and reduction in light penetration also occur at higher densities (Rees, 1974). The morphogenic effects of high planting densities may not be seen in the first year because the bulb has sufficient carbohydrate reserves, but future crops may exhibit lower productivity and stem-quality issues (Rees, 1974) making it important to look at the long-term effects of planting densities on perennials. Effects of planting density have not been investigated for pineapple lily.

Growth and flowering of most geophytes is controlled by internal physiological factors, such as dormancy, maturity, bulb storage condition, and forcing temperatures (De Hertogh and Le Nard, 1993). Storage temperature affects the formation of floral organs and the timing of flowering (Hartsema, 1961). In general, temperature is the major environmental factor that influences the flowering process from flower initiation to development in bulb plants (Roh and Hong, 2007). Both temperature and photoperiod are known to affect the formation of floral organs in oriental lily [*Lilium longiflorum* (Roh and Wilkins, 1978)]. Closely related to pineapple lily, star-of-bethlehem (*Ornithogalum thyrsoides*) has a relatively shallow dormancy and may continue to grow and flower under favorable environmental conditions and will not enter dormancy (Halevy, 1990). Effective temperature for breaking of dormancy may also vary within species. Little information is known about suitable temperatures for dormancy breaking or flower initiation of pineapple lily.

It is also important for growers to know optimal production temperatures before growing a new crop.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
1	ppm	mg·L ⁻¹	1
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Fig. 1. Four cultivars of pineapple lily during field production: (A) Lavender, (B) Sparkling Burgundy, (C) Cream, and (D) Coral.

Each plant species has a range of temperatures that are tolerable and conducive to plant growth, but extreme temperatures within that range can stress plants resulting in pest/disease problems, unacceptably long production times, or reduced inflorescence quality (Dole and Wilkins, 2005). Growers may have access to different production environments depending on their individual operations. It is important to understand the differences these production environments will have on the productivity and quality of cut stems.

The objectives of this study were to determine the optimal production environment, planting density, bulb storage duration and temperature, and forcing temperature for 'Coral', 'Cream', 'Lavender', and 'Sparkling Burgundy' pineapple lily.

Materials and methods

PRODUCTION ENVIRONMENT $\times$ PLANTING DENSITY. Bulbs of 'Coral', 'Cream', and 'Lavender' pineapple lily were received from a commercial

supplier on 14 May 2009 and held overnight. 'Sparkling Burgundy' was dug and divided from field beds at North Carolina State University. Bulbs were all planted on 15 May 2009 and grown in either a double-layered polyethylene-covered greenhouse or loamy clay soil field beds (3×180 ft) in Raleigh, NC. In the greenhouse, bulbs were planted in lily crates ($22 \times 14.5 \times 9$ inches) using a commercial peat-based root substrate (Fafard 4P Mix; Fafard, Agawam, MA) and grown at 20 ± 5 °C night temperatures and ambient air temperatures during the day. In the greenhouse, plants were fertigated with 250 ppm nitrogen (N) from a premixed commercial 20N-4.4P-16.6K fertilizer (Peter's, Allentown, PA) when the substrate was dry, but the plant had not wilted. Clear water was used on the weekends. Bulbs in each production environment were planted at a low density of six bulbs per crate (5×7 -inch spacing between bulbs) or a high density of 12 bulbs per crate (4×4 -inch spacing). The

equivalent spacing was replicated in the field. This resulted in a 2×2 factorial (2 production environments $\times$ 2 planting densities) arranged in a completely randomized design with 10 replications (crates/field plots) per treatment for 'Coral', 'Cream', and 'Lavender' and two replications per treatment for 'Sparkling Burgundy'. Stem length and caliper, and number of marketable stems per replication were recorded. Stems were considered marketable if they were greater than 30 cm in length and had typical inflorescence morphology (multiple leaf-like bracts on top of inflorescence with ovate buds and star-shaped flowers along a smooth stem).

LONG-TERM PLANTING DENSITY. For the bulbs planted in the field in 2009, data on stem length, caliper, and the number of marketable stems per plot were recorded for 2010 and 2011 for all cultivars.

BULB STORAGE $\times$ FORCING TEMPERATURE. Bulbs of 'Coral', 'Cream', and 'Lavender' grown in the greenhouse from 2009 were no longer watered once flower production ceased and on 9 Sept. 2009, the foliage was removed from all bulbs in one crate per cultivar per density treatment and then stored in one of the following treatments: 1–4) bulbs lifted and placed into paper bags in a dark 13 ± 2 °C cooler for either 47, 54, 80, or 96 d; 5) bulbs remained in substrate and cooled in a dark 13 ± 2 °C cooler for 47 d; 6) bulbs left in greenhouse at 18 ± 3 °C night/ 24 ± 4 °C day temperatures for 47 d; 7) bulbs stored outside at 3 ± 4 °C night/ 16 ± 3 °C day temperatures for 47 d.

Bulbs were replanted after storage into lily crates in the same manner as above, except that all bulbs were planted at six bulbs per crate. Bulbs that were stored in substrate remained in the substrate undisturbed. One crate from each storage treatment was placed into double-layered polyethylene-covered greenhouses set to one of three temperature regimes: 1) 18 ± 4 °C night/ 22 ± 5 °C day, 2) 10 ± 2 °C night/ 14 ± 5 °C day, or 3) 2 ± 3 °C night/ambient air temperatures during the day. Shoot emergence per crate and shoot height were recorded on 16 Mar. 2010. Stem length and caliper, and number of marketable stems per replication were also recorded. Stems were

deemed marketable as indicated above.

STATISTICAL ANALYSIS. Data were analyzed using analysis of variance (ANOVA) using the general linear model (GLM) procedure and means separated by Tukey's multiple comparison procedure at $\alpha = 0.05$ using SAS (version 9.3; SAS Institute, Cary, NC). The crate or plot was used as the experimental unit. For long-term planting density data were analyzed using repeated measures ANOVA using plot as the experimental unit and means were separated using least significant differences at $\alpha = 0.05$.

Results

Production environment $\times$ density

ALL CULTIVARS. In year 1 'Sparkling Burgundy' had the longest stem length of 61.7 cm and 'Lavender' had the shortest of 40.9 cm, while 'Coral' and 'Cream' were intermediate at 53.2 and 53.4 cm, respectively ($P < 0.001$). 'Cream' and 'Sparkling Burgundy' had the thickest stem calipers of 15.4 and 15.3 mm, respectively; 'Lavender' had the thinnest of 10.2 mm and 'Coral' was intermediate at 12.7 mm ($P < 0.001$). 'Coral' and 'Cream' produced the most stems per bulb of 1.2 and 1.0, respectively, while, 'Lavender' and 'Sparkling Burgundy' produced the least of 0.6 and 0.6, respectively ($P < 0.001$). Since there were significant differences among cultivars, they were further analyzed separately.

'CORAL'. Planting environment and density interacted such that bulbs in the field at the low density resulted in the shortest stem length of 46.5 cm, while bulbs in the greenhouse at the low density had the longest stem length of 58.8 cm, which did not differ from bulbs in the greenhouse at the high density of 56.9 cm ($P < 0.001$). Stems in the field planted at the high density were intermediate in stem length at 49.8 cm. Stem caliper in the field at both planting densities did not differ from one another with 12.1 mm at the low density and 11.8 mm at the high density, but stem calipers at each density were significantly lower than those in the greenhouse, 14.0 and 12.9 mm, respectively. The number of marketable stems per plant was 1.3 when planted at the low density and 1.1 at the high density. Neither production environment nor the interaction of

environment and planting density had an effect on the number of marketable stems.

'CREAM'. Planting environment and density interacted such that stems in the field at the low density resulted in the shortest stem length of 36.7 cm, while stems in the greenhouse at the low density had the longest stem length of 53.8 cm, which did not differ from bulbs in the greenhouse at the high density of 53.2 cm ($P = 0.021$). Stems in the field planted at the high density were intermediate in stem length at 39.2 cm. Stem caliper in the field at both planting densities did not differ from one another with 13.8 mm at the low density and 13.1 mm at the high density, but stem calipers at each density were significantly lower than those in the greenhouse ($P = 0.039$), 16.5 and 14.8 mm, respectively. Bulbs planted in the greenhouse had more marketable stems per plant (1.1) than those planted in the field (0.9). Neither planting density nor the interaction of planting density and environment had an effect on the number of marketable stems.

'LAVENDER'. Stem length was greater in the greenhouse at 44.0 cm than in the field at 38.1 cm ($P = 0.021$) and unaffected by planting density. Stem caliper was reduced from 11.1 mm in the low density to 9.8 mm in the high density ($P < 0.001$) and unaffected by production environment. Neither planting density nor production environment had an effect on marketable stem number. There were no significant interactions.

'SPARKLING BURGUNDY'. Stem length and caliper were greater in the greenhouse (68.6 cm and 16.4 mm,

respectively) than in the field (54.5 cm and 14.5 mm, respectively) ($P < 0.001$ and $P = 0.025$, respectively). Neither planting density nor production environment affected marketable stem number. Planting density did not affect any parameters measured and there were no significant interactions.

Long-term planting density

ALL CULTIVARS. Differences existed among cultivars for stem length ($P < 0.001$) and number of marketable stems per bulb ($P < 0.001$) so the cultivars were analyzed separately for further interpretation of the effects of long-term planting densities (Table 1). Stem caliper did not differ among cultivars.

'SPARKLING BURGUNDY'. Over the 3 years the number of marketable stems per bulb increased ($P = 0.033$; Table 2). Stem length was affected by year such that it significantly increased from 2009 to 2010 and then decreased from 2010 to 2011 ($P = 0.007$; Table 3). No significant interactions occurred between density and year. Stem caliper was not influenced by density or year.

'CORAL'. Planting density affected the number of marketable stems per bulb with the low-density plantings yielding 2.5 stems per bulb and the high-density plantings yielding 2.1 stems per bulb ($P < 0.001$). Stem caliper was greater in the low-density plantings (13.5 mm) compared with the high-density plantings (12.8 mm) ($P = 0.033$). Over the 3 years, the number of marketable stems per bulb significantly increased (Table 2). Stem length (Table 3) and diameter (Table 4) were affected by year such that both significantly

Table 1. Effect of cultivar on stem length and marketable stems averaged over 3 years of production on 'Sparkling Burgundy', 'Coral', 'Cream', and 'Lavender' pineapple lily. A stem was considered marketable if it was at least 30 cm long and had no abnormal development.

Cultivar	Stem length (cm) ^a	Stems (no./bulb)
Sparkling Burgundy	75.4 a ^b	1.0 b
Coral	60.2 c	2.3 a
Cream	50.6 d	1.5 b
Lavender	65.5 b	1.5 b
Significance ^x	<0.001	<0.001

^a1 cm = 0.3937 inch.

^bMeans followed by the same letter are not significantly different according to least significant differences procedure at $\alpha = 0.05$.

^xProbability values were obtained using repeated measures analysis of variance of SAS (version 9.3; SAS Institute, Cary, NC).

increased from 2009 to 2010 and then decreased from 2010 to 2011 ($P < 0.001$). In addition, there was a significant interaction between year and density affecting stem length and the number of marketable stems ($P = 0.006$; Table 5).

‘CREAM’. Year affected the number of marketable stems per bulb causing it to increase from year to year ($P < 0.001$; Table 2). Year also affected stem length in that it increased from 2009 to 2010 and then decreased from 2010 to 2011 ($P < 0.001$; Table 3). In addition, stem caliper decreased from 2010 (13.1 mm) to 2011 (10.5 mm) ($P < 0.001$; Table 4). Stem caliper was greater in the low-density planting (12.8 mm) compared with the high-density planting (11.9 mm) ($P = 0.001$). There were no significant interactions between year and density. Density did not influence the number of marketable stems per bulb.

‘LAVENDER’. The number of marketable stems per bulb increased from year to year (Table 2). From 2009 to 2010 stem length (Table 3) and caliper (Table 4) increased significantly and from 2010 to 2011 there were no significant changes. The greater planting density decreased stem caliper from 14.5 to 13.0 mm ($P = 0.011$). There were no significant interactions between density and year. Density did not affect the number of marketable stems per bulb.

Bulb storage temperature and duration $\times$ forcing temperature

‘CORAL’. The tallest shoots of 25.9 cm were from bulbs stored for 47 d outside in the substrate and forced at 18 °C (Table 6). This treatment also had the greatest number of shoots emerged per bulb of 3.2. Bulbs stored for 47 d in substrate in the greenhouse and forced at 18 °C were the second-most productive and had a shoot height of 19.8 cm. However, these shoot heights did not differ from bulbs stored for 96 d in the cooler removed from the substrate and forced at 18 °C (18.5 cm). The least number of shoots per bulb (0.2) was in the treatment stored for 54 d in the cooler removed from the substrate and forced at 2 °C.

Bulbs forced at 18 °C had a shorter stem length of 50.8 cm compared with bulbs forced at 10 and 2 °C, which had lengths of 55.6

and 53.9 cm, respectively. The 2 °C forcing temperature resulted in the thickest stem caliper of 13.5 mm. The

10 and 18 °C temperatures both resulted in a 12.1-mm caliper. Days to flowering were also reduced in the

Table 2. Effects of year on marketable stems for ‘Sparkling Burgundy’, ‘Coral’, ‘Cream’, and ‘Lavender’ pineapple lily. A stem was considered marketable if it was at least 30 cm (11.8 inches) long and had no abnormal development.

Yr	Sparkling Burgundy	Coral	Cream	Lavender
	Marketable stems (no./bulb)			
2009	0.6 b ^z	1.2 c	1.0 c	1.0 c
2010	1.1 ab	2.4 b	1.9 a	1.5 b
2011	1.4 a	3.4 a	1.6 b	1.8 a
Significance ^y	0.033	<0.001	<0.001	<0.001

^zMeans followed by the same letter are not significantly different according to least significant differences procedure at $\alpha = 0.05$.

^yProbability values were obtained using repeated measures analysis of variance of SAS (version 9.3; SAS Institute, Cary, NC).

Table 3. Effects of year on stem length of ‘Sparkling Burgundy’, ‘Coral’, ‘Cream’, and ‘Lavender’ pineapple lily.

Yr	Sparkling Burgundy	Coral	Cream	Lavender
	Stem length (cm) ^z			
2009	54.8 b ^y	48.3 c	37.9 c	43.0 b
2010	84.1 a	64.6 a	56.9 a	72.5 a
2011	78.1 a	61.2 b	49.4 b	76.1 a
Significance ^x	0.007	<0.001	<0.001	<0.001

^z1 cm = 0.3937 inch.

^yMeans followed by the same letter are not significantly different according to least significant differences procedure at $\alpha = 0.05$.

^xProbability values were obtained using repeated measures analysis of variance of SAS (version 9.3; SAS Institute, Cary, NC).

Table 4. Effect of year on stem caliper of ‘Coral’, ‘Cream’, and ‘Lavender’ pineapple lily planted at two different planting densities (6 or 12 bulbs/plot).

Yr	‘Coral’	‘Cream’	‘Lavender’
	Stem caliper (mm) ^z		
2009	12.1 c ^y	13.4 a	10.0 b
2010	14.2 a	13.1 a	14.8 a
2011	13.2 b	10.5 b	14.6 a
Significance ^x	<0.001	<0.001	<0.001

^z1 mm = 0.0394 inch.

^yMeans followed by the same letter are not significantly different according to least significant differences procedure at $\alpha = 0.05$.

^xProbability values were obtained using repeated measures analysis of variance of SAS (version 9.3; SAS Institute, Cary, NC).

Table 5. Effects of the interaction of planting density and year on stem length and number of marketable stems of ‘Coral’ pineapple lily. The low-density plantings were 6 bulbs/plot and high-density plantings were 12 bulbs/plot.

Planting density	Yr	Stem length (cm) ^z	Marketable stems (no./bulb)
Low	2009	46.5 e ^y	1.3 f
	2010	64.1 ab	2.4 d
	2011	62.3 bc	3.9 c
High	2009	49.8 d	1.1 e
	2010	65.3 a	2.4 b
	2011	60.1 c	2.9 a
Significance ^x		0.012	0.006

^z1 cm = 0.3937 inch.

^yMeans followed by the same letter are not significantly different according to least significant differences procedure at $\alpha = 0.05$.

^xProbability values were obtained using repeated measures analysis of variance of SAS (version 9.3; SAS Institute, Cary, NC).

Table 6. Effect of forcing temperature and bulb storage treatment on the shoot height and shoot emergence of 'Coral', 'Cream', and 'Lavender' pineapple lily. Once flower production ceased, bulbs were stored in one of the following treatments: bulbs lifted and placed into paper bags in the dark at 13 ± 2 °C (cooler) for either 47, 54, 80, or 96 d or bulbs remained in substrate and placed in the dark at 13 ± 2 °C for 47 d, left in greenhouse for 47 d, or stored outside for 47 d. After storage, bulbs were planted and forced at either 2, 10, or 18 °C in a greenhouse. Shoot emergence and height were recorded on 16 Mar. 2010.

Forcing temp (°C) ^z	Storage treatment			Coral		Cream		Lavender	
	Lifted	Duration (d)	Environment ^y	Shoot ht (cm) ^z	Shoots emerged (no./bulb)	Shoot ht (cm)	Shoots emerged (no./bulb)	Shoot ht (cm)	Shoots emerged (no./bulb)
2	Yes	96	Cooler	2.5 ef ^x	1.5 gh	0 b	0.0 c	1.1 c	0.5 efgh
		80		2.6 ef	1.0 ij	0 b	0.0 c	0.5 d	0.2 gh
		54		1.4 f	0.2 l	0 b	0.0 c	1.2 c	0.1 h
		47		1.2 f	0.6 k	0 b	0.0 c	1.0 c	0.1 h
	No		Greenhouse	—	—	—	—	1.3 c	0.1 h
			Cooler	2.0 ef	0.8 jk	0 b	0.0 c	—	—
			Outside	5.5 ef	1.9 ef	3.0 a	0.0 c	—	—
			Cooler	5.0 ef	1.2 hi	0 b	0.0 c	5.5 b	0.2 gh
				4.0 ef	1.7 fg	0 b	0.0 c	4.5 b	1.0 bcde
10	Yes	96	Cooler	2.2 ef	1.0 ij	0 b	0.0 c	1.5 c	0.2 gh
		80		1.5 f	0.8 jk	1.5 a	0.1 c	1.5 c	0.4 fgh
		54		4.0 ef	1.7 fg	1.5 a	0.1 c	—	—
		47		6.9 def	2.4 bc	—	—	5.3 b	1.3 abc
	No		Greenhouse	—	—	—	—	6.8 b	1.2 bcd
			Cooler	18.5 b	2.2 cde	1.4 a	0.5 b	12.8 a	1.2 bcd
			Cooler	14.4 bc	2.7 b	7.1 a	1.2 a	15.3 a	1.2 bcd
				12.2 cd	2.0 def	1.8 a	0.5 b	13.6 a	0.7 defg
		47	Outside	7.8 de	2.4 bcd	0 b	0.0 c	9.6 b	1.9 a
18	Yes	96	Cooler	19.8 ab	2.5 bc	0 b	0.0 c	—	—
		80		—	—	5.3 a	1.2 a	15.3 a	1.5 ab
		54		25.9 a	3.2 a	—	—	12.5 a	0.8 cdef
		47		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	No		Greenhouse	—	—	—	—	—	—

^z(1.8 × °C) + 32 = °F, 1 cm = 0.3937 inch.

^yGreenhouse = $3 \pm 4/16 \pm 3$ °C (night/day) temperatures, Raleigh, NC, from 1 Nov. 2009 to 14 Dec. 2009; Outside = $18 \pm 3/24 \pm 4$ °C (night/day) temperatures, unheated double-layered polyethylene-covered greenhouse.

^xMeans followed by the same letter are not significantly different according to Tukey's multiple comparison procedure at $\alpha = 0.05$.

^wProbability values were obtained using GLM procedures of SAS (version 9.3; SAS Institute, Cary, NC).

18 °C forcing temperature to 176 from 193 d for the 10 °C temperature and 199 d for the 2 °C temperature. The number of marketable stems produced from each bulb in the 18 °C temperature was lower (1.4) than in the 2 and 10 °C temperatures (1.8 and 1.9, respectively). Temperature did not affect the number of marketable stems.

Bulbs stored for 47 d in the greenhouse in the substrate and grown at 18 °C produced the shortest stem length of 43.5 cm, whereas those stored in the same manner but grown at 10 °C had the longest stem length of 62.5 cm (Table 7). The thinnest stem caliper of 10.7 mm was also produced by the bulbs stored for 47 d in the greenhouse in the substrate and grown at 18 °C. The thickest stem calipers of 14.5 and 14.7 mm were from bulbs stored for 47 d in the cooler in the substrate and grown at 2 °C and stored for 80 d in the cooler removed from the

substrate and grown at 2 °C, respectively. The number of marketable stems was lowest for bulbs stored for 47 d in the greenhouse in the substrate and grown at 18 °C (76%). Bulbs stored for 96 d in the cooler removed from the substrate and grown at 10 °C as well as those stored for 47 d outside in the substrate had similar marketability of 78% and 79%, respectively. The highest number of stems per bulb of 2.3 was produced by bulbs stored for 47 d outside in the substrate and grown at 18 °C. Days to flowering was least for bulbs stored for 96 d in the cooler removed from the substrate and grown at 18 °C (162 d). Days to flowering was greatest for bulbs stored for 47 or 54 d in the cooler removed from the substrate and grown at 2 °C (207 and 205 d, respectively).

'CREAM'. The greatest shoot length (5.3 cm) and number of shoots per bulb (1.2) were from bulbs stored for 47 d in the cooler in the

substrate and forced at 18 °C (Table 6). 'Cream' had the least emergence of all the cultivars and was very slow growing in general.

The 2 °C forcing temperature significantly reduced stem length to 47.7 cm from 52.9 cm for 10 °C and 52.6 cm for 18 °C. The number of marketable stems produced per bulb was greatest in the 10 °C temperature (0.9), least in the 18 °C temperature (0.5), and moderate in the 2 °C temperature (0.7). Days to flower was shortest at the 18 °C forcing temperature (201 d) and longest in the 2 °C and 10 °C temperatures (213 and 209 d, respectively). Temperature did not affect stem caliper.

The smallest number of stems per bulb of 0.1 was produced by the bulbs stored for 96 d in the cooler removed from the substrate and grown in 2 °C production temperature (Table 8). The greatest number of stems per bulb of 1.3 was produced by bulbs stored for 47 d outside

Table 7. Effect of production temperature and bulb storage treatment of 'Coral' pineapple lily on stem length, caliper, number of stems per bulb, days to flower, and number of marketable stems. Bulbs were stored in one of the following treatments: bulbs lifted and stored at 13 ± 5 °C (cooler) for either 47, 54, 80, or 96 d or bulbs remained in substrate stored at 13 °C, left in greenhouse, or stored outside for 47 d. After storage, bulbs were planted and forced at either 2, 10, or 18 °C in a greenhouse.

Storage treatment				Length (cm) ^z	Caliper (mm) ^z	Stems (no./bulb)	Time to flower (d)	Marketability (%)
Temp (°C) ^z	Removed	Duration (d)	Environment ^y					
2	Yes	96	Cooler	46.1 ef ^x	13.5 abcd	1.4 efg	195 cd	100 a
		80		53.4 bcde	14.7 a	0.8 i	193 cd	86 b
		54		55.9 abcd	12.7 abcde	1.8 cd	205 ab	100 a
		47		55.8 abcd	12.9 abcde	1.8 cde	207 a	93 a
	No		Greenhouse	—	—	—	—	—
			Cooler	48.6 def	14.5 ab	1.6 def	195 cd	79 b
			Outside	57.8 abc	13.9 abc	2.0 abc	196 cd	92 a
10	Yes	96	Cooler	52.0 bcdef	11.3 de	1.0 hi	180 f	78 b
		80		58.2 abc	12.5 abcde	1.1 ghi	190 de	100 a
		54		57.8 abc	12.5 abcde	1.2 gh	196 cd	100 a
		47		52.3 bcdef	11.5 cde	1.9 bcd	198 bc	100 a
	No		Greenhouse	62.5 a	14.3 ab	1.1 ghi	190 cde	100 a
			Cooler	59.2 ab	12.7 abcde	2.2 ab	189 de	100 a
			Outside	—	—	—	—	—
18	Yes	96	Cooler	50.8 bcdef	13.2 abcde	1.0 hi	162 i	100 a
		80		50.2 cdef	12.2 abcde	1.3 fgh	171 gh	100 a
		54		46.7 ef	12.6 abcde	1.1 ghi	177 fg	100 a
		47		58.3 abc	11.9 bcde	1.4 efg	184 ef	100 a
	No		Greenhouse	43.5 f	10.7 e	1.4 efg	179 f	76 b
			Cooler	—	—	—	—	—
			Outside	44.2 f	13.2 abcde	2.3 a	166 hi	93 a
Significance ^w				<0.001	<0.001	<0.001	0.001	0.005

^z(1.8 × °C) + 32 = °F, 1 cm = 0.3937 inch, 1 mm = 0.0394 inch.

^yGreenhouse = $3 \pm 4/16 \pm 3$ °C (night/day) temperatures, Raleigh, NC, from 1 Nov. 2009 to 14 Dec. 2009; Outside = $18 \pm 3/24 \pm 4$ °C (night/day) temperatures, unheated double-layered polyethylene-covered greenhouse.

^xMeans followed by the same letter are not significantly different according to Tukey's multiple comparison procedure at $\alpha = 0.05$.

^wProbability values were obtained using GLM procedures of SAS (version 9.3; SAS Institute, Cary, NC).

in the substrate and grown at 2 °C. The interaction between bulb storage treatment and production temperature did not affect stem length, caliper, marketability, or days to flower.

'LAVENDER'. Bulbs grown at 18 °C and either stored for 47 d in the cooler in the substrate or grown at 18 °C had the greatest emergence of 15.3 cm and 1.5 shoots per bulb (Table 6). The greatest number of shoots per bulb was 1.9 from the bulbs stored for 47 d in the cooler removed from the substrate and grown at 18 °C.

Bulbs forced at 10 °C produced the longest stem length of 76.3 cm, while bulbs at the 2 and 18 °C temperatures produced stem lengths of 64.6 and 59.6 cm. Stem marketability declined as temperatures went from 2 (100%) to 10 (94%) to 18 °C (88%). Days to flower was least in the 18 °C temperature at 190 d, 10 °C at 199 d, and 2 °C at 208 d. The number of stems per bulb was also

greatest in the 2 °C forcing temperature at 0.8. The 10 and 18 °C declined to 0.7 and 0.6 stems per bulb. Forcing temperature did not affect stem caliper.

Bulbs stored for 54 d in the cooler removed from the substrate and grown in 10 °C production temperature and had the shortest flowering time of 171 d (Table 9). Bulbs stored for 54 d in the cooler removed from the substrate and grown at 2 °C had the longest flowering time of 212 d. Bulbs stored for 47 d in the cooler in the substrate and grown at 10 °C had the greatest number of marketable stems per bulb of 1.8. Bulbs stored for 96 and 80 d in the cooler removed from the substrate produced no stems. The interaction of bulb storage treatment and production temperature did not affect stem length and caliper.

Discussion

All of the pineapple lily cultivars in this study could be grown in either

the open field or greenhouse and produce marketable stems. This allows growers the flexibility to choose which environment best suits their needs. Growers with limited field space could produce a crop in the greenhouse in ≈ 2 months when planted in May without a large space commitment, while those with field space available for one or several years could benefit from the perennial plantings. Stems were consistently longer in the greenhouse than in the field, which may be due to the reduced light intensity or air movement from the plastic covering on the greenhouse (Wien, 2009). Ortiz et al. (2012) also found the stem lengths of two snapdragon (*Antirrhinum majus*) cultivars, lisianthus (*Eustoma russellianum*), sunflower (*Helianthus annuus*), stock (*Matthiola incana*), and zinnia (*Zinnia elegans*) to be longer in a high tunnel compared with those that were field grown. Stem caliper was also greater in the greenhouse than in the field.

Table 8. The effect of bulb storage treatment and production temperature of ‘Cream’ pineapple lily on number of stems per bulb. Once flower production ceased, bulbs were stored in one of the following treatments: bulbs lifted and placed into open plastic bags in the dark at $13 \pm 5^\circ\text{C}$ (cooler) for either 47, 54, 80, or 96 d or bulbs remained in substrate and placed in the dark at 13°C for 47 d, left in greenhouse for 47 d, or stored outside for 47 d. After storage, bulbs were planted and forced at either 2, 10, or 18°C in a greenhouse.

Storage treatment					
Temp (°C) ^z	Removed	Duration (d)	Environment ^y	Stems (no./bulb)	
2	Yes	96	Cooler	0.1 f ^x	
		80		0.3 ef	
		54		0.7 cd	
		47		0.7 bcd	
	No		Greenhouse	—	
				Cooler	0.8 bc
				Outside	1.3 a
10	Yes	96	Cooler	0.6 cde	
		80		0.6 cde	
		54		0.3 def	
		47		1.1 ab	
	No		Greenhouse	0.6 cde	
				Cooler	—
				Outside	0.8 bc
18	Yes	96	Cooler	0.6 cde	
		80		0.4 cdef	
		54		0.4 cdef	
		47		0.6 cde	
	No		Greenhouse	0.5 cdef	
				Cooler	0.8 bc
				Outside	—
Significance ^w				<0.001	

^z($1.8 \times ^\circ\text{C}$) + 32 = $^\circ\text{F}$.

^yGreenhouse = $3 \pm 4/16 \pm 3^\circ\text{C}$ (night/day) temperatures, Raleigh, NC, from 1 Nov. 2009 to 14 Dec. 2009; Outside = $18 \pm 3/24 \pm 4^\circ\text{C}$ (night/day) temperatures, unheated double-layered polyethylene-covered greenhouse.

^xMeans followed by the same letter are not significantly different according to Tukey's multiple comparison procedure at $\alpha = 0.05$.

^wProbability values were obtained using GLM procedures of SAS (version 9.3; SAS Institute, Cary, NC).

An increase in stem length and caliper usually equates to better stem strength and higher quality cuts (Ortiz et al., 2012). This suggests that it may be beneficial to grow pineapple lily in a high tunnel or under a shade structure. The extra protection early in the season may also help to reduce time to flowering. The high planting density would be ideal for greenhouses with limited space since more stems per unit area could be obtained. This study shows that planting up to 12 bulbs per lily crate did not severely affect stem quality. Field production may be better served by low planting densities to facilitate subsequent years' bulb offsets. In the field, the higher density increased stem length. This is similar to calla lily (*Zantedeschia aethiopica*) where close planting densities increased stem length and did not affect the number of flowers produced (Luria et al., 2005).

Three years of production information gave us valuable data for effects of the two different planting densities long term. Stem quality (length and caliper) increased for all cultivars from 2009 to 2010, but did not change significantly from 2010 to 2011. ‘Coral’ was an exceptional cultivar that increased productivity and stem quality every year regardless of the planting density, but the low planting density had one more stem per bulb than the high planting density. ‘Sparkling Burgundy’ and ‘Lavender’ increased production without reducing quality at both densities over the three seasons, while ‘Cream’ production slightly decreased for both planting densities. For the long term, bulbs should be planted at a wider spacing and lower planting density to give the bulblets from the original mother bulb room to grow and access to resources.

As seen in this study, the flowering of pineapple lily depended greatly on temperature. Bulbs in the 18°C production temperature emerged faster and flowered sooner than those in the cooler temperatures. Flower initiation in pineapple lily could be caused by a critical temperature and duration, which when reached, halts stem elongation and causes the inflorescence to mature. This would account for the shortened stem length in the warmest production temperature. In addition, the shortened stem lengths were not significant enough to affect marketability, which was defined as having a stem length of at least 30 cm and no malformations. While it is beneficial to have cut flowers available early in the season for Easter and Mother's Day sales, the extra costs associated with heating a greenhouse to speed flowering may or may not be worth the benefits.

Fast-growing cultivars like Coral, which had the greatest emergence and was the first to flower in the field and greenhouse, would be ideal to hasten the time to flowering. Not considering the cultivar and production temperature, bulbs stored in the substrate either outside or in the cooler had greater shoot numbers and shoot lengths. The faster shoot growth of bulbs stored in substrate compared with bulbs removed from the substrate was most likely due to the root system remaining intact. A clear trend in ‘Coral’ emergence occurred in all production temperatures resulting in bulbs removed from the substrate, as storage time increased shoot height also increased. Roh et al. (2007) found that the speed of leaf emergence of star-of-bethlehem can be used to measure the level of dormancy, as well as in oriental lily (De Hertogh et al., 1971). Our data suggest that the bulbs harvested first and stored the longest (96 d) were the least dormant and that the dormancy decreased as storage length increased.

Pineapple lily benefits from a cold period, which may be cumulative and facultative. These characteristics would be an added benefit to field production since bulbs do not need to be dug after the production season, as long as they were being grown in the appropriate zone, and would undergo natural vernalization while overwintering. Most pineapple lilies

Table 9. The effect of bulb storage treatment and production temperature on the number of stems per bulb of ‘Lavender’ pineapple lily. Once flower production ceased, bulbs were stored in one of the following treatments: bulbs lifted and placed into open plastic bags in the dark at 13 ± 5 °C (cooler) for either 47, 54, 80, or 96 d or bulbs remained in substrate and placed in the dark at 13 °C for 47 d, left in greenhouse for 47 d, or stored outside for 47 d. After storage, bulbs were planted and forced at either 2, 10, or 18 °C in a greenhouse.

Storage treatment							
Temp (°C) ^z	Removed	Duration (d)	Environment ^y	Marketability (%)	Time to flower (d)	Stems (no./bulb)	
2	Yes	96	Cooler	100 a ^x	199 abcd	0.2 f	
		80		100 a	205 abc	0.6 cde	
		54		100 a	212 a	0.4 def	
		47		100 a	207 ab	0.8 bc	
	No		Greenhouse	100 a	211 a	0.9 b	
				Cooler	—	—	—
				Outside	—	—	—
10	Yes	96	Cooler	75 a	202 abc	0.4 def	
		80		67 a	190 bcde	0.3 ef	
		54		100 a	205 abc	0.3 ef	
		47		100 a	207 ab	0.3 ef	
	No		Greenhouse	—	—	—	
				Cooler	100 a	193 abcd	1.8 a
				Outside	100 a	203 abc	0.8 bc
18	Yes	96	Cooler	0 b	0 f	0.0 g	
		80		0 b	0 f	0.0 g	
		54		0 b	171 e	0.1 f	
		47		100 a	186 cde	0.3 ef	
	No		Greenhouse	—	—	—	
				Cooler	100 a	182 de	0.4 def
				Outside	75 a	204 abc	0.7 bcd
Significance ^w				<0.001	0.001	<0.001	

^z(1.8 × °C) + 32 = °F.

^yGreenhouse = 3 ± 4/16 ± 3 °C (night/day) temperatures, Raleigh, NC from 1 Nov. 2009 to 14 Dec. 2009; Outside = 18 ± 3/24 ± 4 °C (night/day) temperatures, unheated double-layered polyethylene-covered greenhouse.

^xMeans followed by the same letter are not significantly different according to Tukey's multiple comparison procedure at $\alpha = 0.05$.

^wProbability values were obtained using GLM procedures of SAS (version 9.3; SAS Institute, Cary, NC).

are hardy to Zone 8 (Bryan and Griffiths, 1995); however, these hybrids have been shown to be hardy in Raleigh, NC (Zone 7b). Studies at Cornell University have shown other pineapple lily hybrids to be hardy in Zone 5 in unheated high tunnels or mulched (W.B. Miller, personal communication). Our emergence data suggests that it may be cumulative because for some cultivar bulbs stored for longer periods at warmer temperatures had similar emergence heights to bulbs stored for shorter periods at colder temperatures. Our flowering data has similar trends; for example, ‘Cream’ pineapple lily stored outside (5 °C) for 47 d and stored in the cooler (13 °C) for 96 d flowered at the same time. ‘Lavender’ pineapple lily may require more chilling hours than the other cultivars according to its change in stem marketability. As the production temperature decreased, the number of marketable stems increased to 100% regardless of storage treatment. This may be due to the 2 °C house staying colder

longer, allowing it to fulfill its chilling requirement better than in warmer houses. This cold requirement does not appear to be obligatory since the treatments that were not cooled (stored in a greenhouse) still flowered with marketable stems.

The combination of being removed from the substrate, stored for long lengths of time and then grown in high temperatures may not have allowed for sufficient root formation and could account for the lack of flowering in the two treatments stored for 96 or 80 d in the cooler removed from the substrate and grown at 18 °C. Amaryllis (*Hippeastrum*) will not flower if the bulbs were harvested when physiologically immature, not stored long enough, improperly stored after harvest, or have a poor root system (De Hertogh, 1996). Lee and Roh (2001) found that high greenhouse forcing temperatures during the summer accelerates flowering, resulting in short plants, and increased number of abnormal flowers in oriental hybrid lilies

‘Acapulco’ and ‘Simplon’ after frozen storage.

Conclusion

Successful production of pineapple lily can be achieved in different production scenarios. Even with the changes in stem length and caliper from the different production environments, planting densities, and production year, the stems were still of marketable quality that would be suitable for cut flowers. Knowing the effects these factors can have on stem quality is important for growers so they can anticipate changes in their product. Pineapple lily is well suited for field or greenhouse production and may also be appropriate for unheated high tunnels. It may be grown for one season in crates in greenhouses or potentially outside or as a perennial in the field in suitable climates. If grown for multiple seasons, a low planting density should be used to allow for subsequent years growth of bulblets. If grown for just one season, a high planting density

has no adverse effects. It would be best for growers to leave bulbs in substrate from season to season and cold store for at least 47 d or dry store in a greenhouse until ready to force. To hasten flowering, warmer forcing temperatures are ideal. Pineapple lily offers growers versatility in production environment and planting density to suit individual needs and still produce marketable stems.

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