Influences of Shading and Fall Fertilization on Fluorescence, Freeze Resistance, Flower Production and Growth of *Rhododendron* ×*kurume* 'Pink Pearl'[1]

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Abstract

We investigated the influences of fall fertilization and light intensity on photosynthesis and freeze resistance of *Rhododendron* ×*kurume* 'Pink Pearl', an evergreen azalea cultivar, grown outdoors in containers under nursery conditions. The study included two main-plot fall fertilization treatments: 1) 0.5 liter solution containing 75 mg·liter^{-1} N applied for 60 days from August 1 through September 29 and 2) 0.5 liter solution containing 125 mg·liter^{-1} N applied for 120 days from August 1 through November 28, and four subplot light intensity treatments 1) 100% ambient photon flux density (*PPFD*) from May 1, 2004, through May 1, 2005, 2) shade fabric rated to reduce *PPFD* by 50% from May 1 through September 30, 2004, followed by 100% *PPFD* from October 1, 2004, through May 1, 2005, 3) 100% *PPFD* from May 1 through September 30, 2004, followed by 50% *PPFD* from October 1, 2004, through May 1, 2005, and 4) 50% *PPFD* from May 1, 2004, through May 1, 2005. Fertilizer application and shade treatments did not interact in their effects on stem freeze resistance or the timing of anthesis. The high rate of extended fertigation (125 mg·liter^{-1} N applied August 1 through September 28) reduced freeze resistance of azalea stems and advanced anthesis by 4.9 days compared to plants that received moderate fertigation (75 mg·liter^{-1} N from August 1 through September 29). The high rate of extended fall fertigation failed to increase leaf or stem dry weight compared to plants that received the moderate rate of fertigation. Plants grown in 50% *PPFD* from May 1 through September 30 produced 163% more above ground dry weight compared to plants grown in 100% light during the same time period. The addition or removal of shade cloth beginning October 1 failed to enhance azalea stem freeze resistance compared to plants that were only exposed to 100 or 50% *PPFD* respectively. Shade treatments affected the chlorophyll fluorescence ratio ($F_v \cdot F_m^{-1}$) of leaves, but leaf fluorescence was unrelated to stem freeze resistance Shade treatments affected azalea growth and photosynthetic stress, but shade neither interacted with fall fertilization to increase stem freeze resistance, nor had a biologically significant effect on stem freeze resistance.

Index words: azalea, container, shade, light, photosynthesis, $F_v \cdot F_m^{-1}$, photoinhibition, chlorophyll, cold, tolerance, hardiness, LT_{50}, nitrogen, SPAD, fertigation, anthesis, flower.

Significance to the Nursery Industry

The high rate of extended fertilization used in this study reduced stem freeze resistance and hastened flowering by nearly 5 days, but failed to increase leaf or stem dry weight compared to plants fertilized with the moderate fertilization regime. Azalea growth increased with the application of shade. However, based on the results of this study, shade fabric (rated to reduce *PPFD* by 50%) has limited influence on freeze resistance. Neither the application of shade fabric immediately after liners were transplanted in spring (May 1), nor shade fabric applied in fall (October 1) had a biologically significant effect on stem freeze resistance (LT_{50}) compared to plants grown in 100% *PPFD*. The ratio of variable to maximum fluorescence ($F_v \cdot F_m^{-1}$) is a rapid non-destructive measure that is inversely proportional to photosynthetic stress and has been used to estimate stem cold hardiness. In this study fluorescence was of limited value as an indicator of freeze resistance, since azalea stem LT_{50} and leaf $F_v \cdot F_m^{-1}$ were unrelated.

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Introduction

Rhododendron species are among the most popular woody flowering landscape shrubs grown in nurseries, landscapes, and ornamental gardens (12, 44). They are often grown under intensive fertilization regimes and are commonly exposed to a wide range of light conditions in their natural habitat (42), in the landscape (4) and in nurseries (4, 21). These divergent fertility and light regimes could influence cold hardiness.

Previous research found that high rates of extended fall fertilization increased azalea growth, but also reduced cold hardiness (20, 45). High rates of fertilization applied in fall were reported to reduce freeze resistance when growth cessation (17, 19) and bud development (17) were delayed in fall, or when new vegetative growth was promoted either late (43, 45) or early (6) in the growing season.

Azaleas that received some shade during the winter were observed to suffer less freeze damage than plants grown in high light intensities (9, 35, 39). Low temperatures inhibit photosynthesis and decrease a plant's photosynthetic quenching capacity because the speed of enzymatic reactions of electron transport and carbon metabolism are reduced, chloroplast membrane function is impaired, or the rate of protein synthesis associated with repair of damaged PSII centers is slowed (40). Shade application in winter decreased photosystem II damage, reduced the incidence and degree of freeze damage and improved *Pseudotsuga menziesii* seedling survival (30). Shade may be useful for reducing freeze damage in nursery production.

Photosynthesis is a useful measure of plant performance because photosynthesis is sensitive to growth factors including temperature, nutrient availability and light (24).

Chlorophyll fluorescence is linearly correlated with the quantum yield of net photosynthesis (1); this fluorescence is an indirect, non-destructive method for assessing photosynthetic performance. The ratio of variable to maximum fluorescence ($F_v \cdot F_m^{-1}$) is a measure of PSII reaction center efficiency that is inversely proportional to photosynthetic stress. Research conducted on *P. menziesii* demonstrated that $F_v \cdot F_m^{-1}$ ratios were linearly related to stem freeze damage and short-term survival after exposure to sub-freezing temperatures (10, 31).

In this publication, the term freeze resistance is used to define the ability or capacity of a plant or plant tissue to survive unfavorable low environmental temperatures (37). The development of freeze resistance is a process that is interdependent with other physiological processes (17, 18). Light intensity (10, 30, 31) and mineral nutrition (20) are known to affect freeze resistance, but little is known about the interactive effects of these variables. Because light intensity and fertility affect freeze resistance, nursery growers may be able to reduce freeze damage and increase flowering and growth of azaleas by managing fertilization and light intensity concomitantly during fall and winter. This study was designed to determine if fall fertilization and shading treatments interact to affect *Rhododendron* ×*kurume* 'Pink Pearl' stem freeze resistance, fluorescence, flower production and shoot growth.

Materials and Methods

On May 1, 2004, 480 uniform *Rhododendron* ×*kurume* 'Pink Pearl' liners were transplanted into 2.2 liter (#1) containers and grown outdoors in a container nursery production area at the University of Georgia's Horticulture Research facility in Athens, GA. Plants were exposed to ambient air temperature that ranged from a summertime high of 35.3C on August 4, 2004, to a wintertime low of –10.9C on January 24, 2005 (95.5 to 12.4F). The growing substrate was aged pine bark amended with 2.37 kg·m^{-3} (4 lb·yd^{-3}) dolomitic limestone and 0.59 kg·m^{-3} (1 lb·yd^{-3}) Micromax micronutrient mix (The Scotts Company, Marysville, OH).

This experiment was a split-plot design with two main-plot fall fertilization treatments, four subplot light intensity treatments, and three replications with 160 plants per replication. High and low *PPFD* subplot light intensity treatments consisted of uncovered hoop house plots and plots covered with black woven polypropylene fabric rated to reduce *PPFD* by 50% (Progress Grower Supply, Canton, GA) respectively. Immediately after liners were transplanted on May 1, 2004, plants were exposed to one of four subplot light intensity treatments 1) low light (50% *PPFD*) from May 1, 2004, through May 1, 2005, 2) low light (50% *PPFD*) May 1 through September 30, 2004, followed by high light (100% *PPFD*) from October 1, 2004, through May 1, 2005, 3) high light (100% *PPFD*) from May 1 through September 30, 2004, followed by low light (50% *PPFD*) from October 1 through May 1, 2005, or 4) high light (100% *PPFD*) from May 1, 2004, through May 1, 2005. Daily *PPFD* was measured throughout the study in high and low light plots using LI-190 sensors (Li-Cor, Lincon, NE) located in covered and uncovered plots. During the course of the study, daily *PPFD* ranged from 1.2 to 47.5 mol·m^{-2}·day^{-1} in high light plots and from 0.7 to 21.7 mol·m^{-2}·day^{-1} in low light plots. Shade fabric reduced daily *PPFD* 43 to 67% compared to the light level of uncovered plots.

The main-plot fertility treatments used in this experiment were chosen based on a previous study conducted by Henning et al. (20), in which a high rate of fertigation (125 mg·liter^{-1} N) extended for 120 days (from August 1 through November 28) increased growth and decreased freeze resistance of *Rhododendron* ×*kurume* compared to plants that received a moderate rate of fertigation (75 mg·liter^{-1} N) that was extended either 60 days (though September 29) or 120 days (through November 28). Prior to the initiation of fertigation treatments on August 1, all plants were fertigated daily with a 0.5 liter (0.13 gal) solution containing 75 mg·liter^{-1} N applied using a constant liquid feed fertilizer application of Harrell's (Sylacauga, AL) 16-3.5-6.6 (N-P-K), N as NO_3 (1.6%), and urea (14.4%). The two main-plot fertigation treatments were initiated August 1, 2004. Plants received either 1) 60 days of extended fertigation from August 1 through September 29 at a moderate rate (75 mg·liter^{-1} N), or 2) 120 days of extended fertigation from August 1 through November 28 at a high rate (125 mg·liter^{-1} N).

To analyze azalea stem freeze resistance, uniform stem sections were harvested from 360 plants, three azaleas per treatment-replication combination, on November 22 and December 21, 2004, and January 19, February 21 and March 22, 2005. Stem sections were only collected one time from each azalea plant that was sampled. Samples from each treatment-replication were combined, wrapped in moist paper towels, sealed in plastic bags, and placed on ice for transport to the lab. Within four hours of collection, stem sections were prepared for freezing. Stem freeze resistance was estimated using the technique outlined by Lindstrom et al. (25). Forty, 5 cm (2 in) long stem segments from each treatment-replication combination were analyzed under laboratory conditions. Four stem segments from each treatment-replication combination were removed from a freezing temperature bath at 3C (5F) temperature intervals. Samples were exposed to temperatures between –3 and –27C (26.6 and –16.6F) for freeze analysis in November, December, and March and to temperatures between –6 and –30C (21.2 and –22F) in January, and February. Four stem segments were kept at 4C (39F) for the duration of the freezing test and used as controls for comparison with frozen samples. The Spearman-Karber Method (11) was used to estimate the freezing temperature at which 50% of stem samples were killed (LT_{50}).

Modulated chlorophyll fluorescence was measured outdoors in experimental plots with a portable fluorometer (pulse amplitude modulated fluorimeter, MINI-PAM Photosynthesis Yield Analyzer, Heinz Walz GmbH, Effeltrich, Germany). Five leaves were analyzed on 120 plants, five randomly selected plants from each treatment-replication combination on December 23, 2004, and January 21, February 23 and March 24, 2005. Readings were taken on the upper most fully expanded, mature leaves located below the terminal bud of hardened new growth. Leaves were analyzed prior to sunrise to ensure that they were dark-adapted and that energy quenching was relaxed. Leaf portions were exposed to a saturating pulse (>8000 µmol·m^{-2}·s^{-1}) to obtain a dark adapted measure of quantum efficiency of photosystem II ($F_v \cdot F_m^{-1}$). MINI-PAM fluorescence measurements were averaged within each treatment-replication combination.

A SPAD-502 chlorophyll meter (Minolta, Ramsey, NJ) estimated total leaf chlorophyll content (26) on the same five plants that were used for fluorescence analysis. SPAD readings were taken on five leaves per plant, midway between

the leaf mid vein and margin, and these measurements were averaged within each treatment-replication combination.

Flower counts began March 1, 2005, prior to anthesis and continued to full flower expression (F_{max}). Flowering was defined as budbreak showing petal color. Flowers were counted three times weekly on the same five plants per treatment-replication combination that were used for fluorescence and chlorophyll analyses. Flower counts were averaged within each treatment-replication combination. Linear regression analysis was then used to characterize the relationship between the day of year and flower count. An equation for the relationship between flower count and day number was developed for each of the 24 treatment-replicate combinations, then the corresponding F_{max} / 2 was used to calculate F_{50} (date which 50% of flowers were in bloom).

The five azaleas from each treatment-replication combination that were used for chlorophyll and flower analysis were harvested May 1, 2005, separated into leaves and stems, and dried at 55C (131F) for 72 h. Leaf, stem and shoot dry weight were determined and averaged within each treatment-replication combination.

In order to monitor changes that occurred over the time period between fall and spring, the interactive effects of fertilization and light intensity treatments on stem freeze resistance, chlorophyll fluorescence and SPAD chlorophyll readings were analyzed using repeated measures GLM procedure (SAS Institute Inc., Cary, NC). Dry weight, flower budbreak and flower production were analyzed using the GLM procedure (SAS Institute Inc., Cary, NC). Tukey's studentized range (HSD) means comparison test at $P \geq 0.05$ was used to detect differences in pairwise comparisons of treatment means.

Results and Discussion

Repeated measures GLM analysis revealed that an interaction between fall fertilization and light intensity treatments was absent and failed to influence azalea freeze resistance and chlorophyll fluorescence. GLM analysis yielded similar results, absence of an interaction for F_{50}, and shoot dry weight. In the absence of interaction, data for the four light intensity treatments were pooled within each fall fertilization treatment and data for the two fertilization treatments were pooled within each light intensity treatment.

The high rate of extended fertilization (125 mg·liter^{-1} N, applied August 1 through November 28) reduced freeze resistance (LT_{50}) of azalea stems from every harvest and reduced LT_{50} of stems harvested November 22 and December 21, 2004, and January 19, February 21, and March 22, 2005, by 6.2, 11.2, 3.9, 4.6, and 5.9C (11.2, 20.1, 7.0, 8.3, and 10.6F) respectively compared to the moderate rate of fertilization (75 mg·liter^{-1} N, applied August 1 through September 30) (Table 1). In a previous study on *Rhododendron* ×*kurume* 'Hinodegiri' that included the same fertilization treatments, the high rate of extended fertilization reduced freeze resistance of azalea stems harvested November 12 and December 11, 2002, and January 14 and March 19, 2003, by 6.3, 11.8, 5.3, and 2.8C (11.3, 21.2, 9.4, and 4.9F) respectively compared to the moderate rate of fertilization (20).

The photosynthetic activity and efficiency of photosystem II ($F_v \cdot F_m^{-1}$) of evergreen species are often reduced by exposure to cold temperatures and consequent cold acclimation (2, 14). Maximal quantum yield of dark-adapted *R.* ×*kurume* leaves in this study were below the expected maximum yield (0.83), but were comparable to values observed by Wang et al. (42) who reported $F_v \cdot F_m^{-1}$ values for *R. ponticum* and *R. catawbiense* of 0.76 and 0.74 for nonacclimated leaves in August, and 0.66 and 0.59 for cold acclimated leaves in November. Nitrogen is a major component of the photosynthetic apparatus, including chlorophyll *a* and *b*, and RuBisCO. Fall fertilization treatments that produced differences in azalea stem LT_{50} had no detectable effect on $F_v \cdot F_m^{-1}$ (data not shown). Consistent with our results for a moderate (75 mg·liter^{-1} N, applied August 1 through September 29) and high rate of extended fertilization (125 mg·liter^{-1} N, applied August 1 through November 28), Birchler (10) detected no differences in chlorophyll fluorescence ($F_v \cdot F_m^{-1}$) of fertilized Douglas fir seedlings that received 80, 160 or 320 kg·ha^{-1} N. The effects of fertilization on fluorescence in this study support Birchler's findings on a conifer species that within the range where N was neither deficient nor toxic, additional N had little effect on light harvesting (10).

Shade removal on October 1 and the associated increase in light intensity failed to enhance azalea freeze resistance compared to plants grown in low light (50% *PPFD*) throughout the study (Table 2). Exposure to low light (50% *PPFD*) from May 1 through September 30, 2004, followed by shade cloth removal and exposure to high light (100% *PPFD*) beginning October 1, produced azaleas that were less freeze resistant on November 22 than plants grown in high light throughout the study (Table 2). These findings contrast with observa-

Table 1. Effects of fall fertigation treatments on pooled[z] freeze resistance (LT_{50}[y]) of stem tissue of *R.* ×*kurume* 'Pink Pearl' grown in Athens, GA.

N fertilizer (mg·liter^{-1} N)		LT_{50} (C, F)				
		Stem harvest dates				
August 1 to September 29	September 30 to November 28	November 22	December 21	January 19	February 21	March 22
75	0	–10.6 (12.9)b[x]	–21.8 (–7.2)b	–24.8 (–12.6)b	–19.5 (–3.1)b	–9.9 (14.2)b
125	125	–4.4 (24.1)a	–10.6 (12.9)a	–20.9 (–5.6)a	–14.9 (5.2)a	–4.0 (24.8)a

[z]Data for the four light intensity treatments were pooled within each fall fertilization treatment because an interaction between fall fertilization and light treatments was absent.

[y]Temperature at which 50% of stems were killed.

[x]Mean separation within columns by Tukey's Studentized range test at $P \leq 0.05$.

Table 2. Effects of light intensity (*PPFD*) on stem tissue freeze hardiness (LT_{50}) of *R.* ×*kurume* 'Pink Pearl'.

Light intensity (% *PPFD*)		LT_{50} (C, F)				
		Stem harvest dates				
May 1 to September 30	October 1 to May 1	November 22	December 21	January 19	February 21	March 22
50	50	–6.6 (20.1)ab[z]y	–14.1 (6.6)a	–24.9 (–12.8)a	–15.8 (3.6)a	–7.9 (17.8)a
50	100	–5.1 (22.8)a	–15.9 (3.4)a	–23.0 (–9.4)ab	–17.1 (1.2)a	–6.5 (20.3)a
100	50	–8.8 (16.2)ab	–17.0 (1.4)a	–21.9 (–7.4)ab	–17.1 (1.2)a	–6.9 (19.6)a
100	100	–9.5 (14.9)b	–17.9 (–0.2)a	–21.6 (–6.9)a	–18.8 (–1.8)a	–6.6 (20.1)a

[z]In the absence of interaction, data from two fertilization treatments were pooled within each light intensity treatment, so that each mean is based on observations of eight stem samples at each of nine different freezing temperature increments for each of three replicates.

[y]Mean separation within columns by Tukey's Studentized range test at $P \leq 0.05$.

tions made on nursery plants grown in North Carolina (9), that shade cloth removal in fall induced more rapid cold acclimation and decreased stem splitting.

In January, azalea stems harvested from plants that only received low light (50% *PPFD*) were more freeze resistant than plants grown in 100% *PPFD* (Table 2). A small difference in stem freeze resistance in January has limited biological significance for most regions of the temperate zone because freeze injury most frequently occurs during the fall or spring when the species has not yet attained its maximum hardiness (43). In addition, fall application of shade (50% *PPFD* on October 1) to plants that were previously grown in high light (100% *PPFD*) failed to affect stem freeze resistance compared to plants that were grown in high light throughout the study. Results from this study contrast with the previous reports by Sweet (39) who found a positive relationship between light intensity and freeze damage (stem splitting) in *Rhododendron* ×*kurume* and *R. simsii* grown in Georgia that were exposed to light intensities that varied from 28 to 100% *PPFD*, by Shumack et al. (35), who observed that azaleas in Alabama that received shade during winter suffered less cold damage, and by Bilderbeck and Bir (9) who noted that nursery plants in North Carolina acclimate to freezing temperatures more slowly in shade than in the sun. These apparent discrepancies in results were attributed to the independent variable that was measured. We measured freeze resistance, whereas these other authors measured, or observed, the incidence and degree of freeze damage (9, 30, 35, 39). Freeze damage reductions associated with shade have been attributed to elevated minimum temperatures, shortened time of exposure to freezing temperatures, and reduced freezing and thawing rates (34), and reduced wind and drought stresses (33). The influence shade has on exposure to stresses that cause freeze damage can be different than the effects shade has on the ability of a plant to survive unfavorable low temperatures.

Treatments that exposed plants to 100% *PPFD* after October 1 resulted in reduced chlorophyll fluorescence $F_v \cdot F_m^{-1}$ ratios in December compared to plants exposed to 50% *PPFD* after October 1 (Table 3). A decline in $F_v \cdot F_m^{-1}$ is a good indicator of photoinhibitory damage (36). One explanation for the photoinhibitory damage (reduced $F_v \cdot F_m^{-1}$ ratios) that we measured in December included the combined photosynthetic stresses of low temperatures and high light intensities that overwhelmed the photosynthetic quenching capacity of azalea photosystems in light treatments. Photoinhibitory damage found in the high light treatments of this study supports research reporting that low temperatures reduce the range of light intensity to which plant photosystems can acclimate (29, 36).

Photoinhibition was higher (the chlorophyll fluorescence $F_v \cdot F_m^{-1}$ ratio was lower) from December through March for azaleas that were grown in 50% *PPFD* between May 1 and September 30 followed by 100% *PPFD* from October 1 through harvest, compared to azaleas that received the converse treatment (100% *PPFD* between May 1 and September 30, followed by 50% *PPFD* from October 1 through harvest). One explanation for these results is acclimation of the xanthophyll cycle (15), which plays a major role in protective energy dissipation when photosynthetic excitation is

Table 3. Effects of light intensity on chlorophyll fluorescence ($F_v \cdot F_m^{-1}$) of *R.* ×*kurume* 'Pink Pearl' leaves.

Light intensity (% *PPFD*)		Chlorophyll fluorescence ratio ($F_v \cdot F_m^{-1}$)			
		Measurement dates			
May 1 to September 30	October 1 to May 1	December 23	January 21	February 23	March 24
50	50	0.70a[zy]	0.67ab	0.67ab	0.68ab
50	100	0.64b	0.59b	0.60a	0.61b
100	50	0.74a	0.72a	0.72a	0.72a
100	100	0.64b	0.63ab	0.65ab	0.65ab

[z]In the absence of interaction, data from two fertilization treatments were pooled within each light intensity treatment, so that each mean is based on observations of five measurements from ten plants in each of three replicates.

[y]Mean separation within columns by Tukey's Studentized range test at $P \leq 0.05$.

Table 4. Effects of daily 0.5 liter fall fertigation and light intensity treatments on *R.* ×*kurume* 'Pink Pearl' SPAD-502 chloropyhll meter reading (SPAD).

N fertilization (mg·liter^{-1} N)		Light intensity (% *PPFD*)		SPAD			
				Measurement dates			
August 1 to September 29	September 30 to November 28	May 1 to September 30	October 1 to May 1	December 23	January 21	February 23	March 24
75	0	50	50	43.4b[zy]	42.6b	40.1b	44.3ab
75	0	50	100	38.5b	37.5b	34.7b	40.6b
75	0	100	50	54.0a	51.2a	47.3a	47.8a
75	0	100	100	43.2b	40.9b	38.6b	42.3ab
125	125	50	50	53.2a	52.0a	50.2a	44.2ab
125	125	50	100	55.2a	52.8a	50.6a	40.0b
125	125	100	50	53.8a	52.5a	53.3a	48.9a
125	125	100	100	55.6a	54.7a	54.0a	44.1ab

[z]Each mean based on observations of five measurements from five plants in each of three replicates.

[y]Mean separation within columns separated by Tukey's Studentized range test at $P \leq 0.05$.

excessive. Demmig-Adams et al. (15) found that leaves that developed in high light contained greater concentrations of xanthophyll cycle components than leaves developed in low light conditions on the same plant.

High light intensities in fall and winter may affect the freeze resistance of plants, particularly evergreens, when excessive excitation of the plant photosynthetic apparatus results in photoinhibition or photoxidation (27). Based on linear correlations between chlorophyll fluorescence ($F_v \cdot F_m^{-1}$) of needles and LT_{50} of Douglas-fir seedling stems that were tested monthly under laboratory conditions, Perks et al. (31) demonstrated that needle $F_v \cdot F_m^{-1}$ is a useful accurate predictor of stem LT_{50}. This work resulted in the development of a fluorescence technique to detect freeze damage, $F.LT_{50}$ (fluorescence-based empirical determination of LT_{50}). Using Pearson's correlation, leaf fluorescence ($F_v \cdot F_m^{-1}$) and LT_{50} were unrelated (r = 0.02) in our study. Fertilization and light treatments affected azalea stem freeze resistance (Tables 1 and 3) and light treatments affected leaf chlorophyll fluorescence (Table 3), but azalea stem freeze resistance and leaf fluorescence were unrelated.

SPAD-502 chlorophyll meter (Minolta, Ramsey, NJ), a non-destructive measure of leaf chlorophyll concentrations (26, 28), and fluorescence ($F_v \cdot F_m^{-1}$), a nondestructive measure of PSII reaction center efficiency (14) lacked a correlation (r = 0.20). These results support those of Olsen et al. (28) who found that chlorophyll concentration were poorly fitted to SPAD readings.

In this study, SPAD readings from azaleas that were grown in 100% *PPFD* throughout the study were similar to those of plants grown in 50% *PPFD* (Table 4). Evidence of photobleaching was not indicated in SPAD readings.

The manufacturer of the SPAD-502 recommends the use of this instrument on leaves with measured values lower than or equal to 50. Values that exceeded 50 were reported in this study, but SPAD data had low standard errors and were tightly clustered.

Nitrogen is an integral component of the photosynthetic apparatus that is linked to photosynthesis and the ability of plants to orderly dissipate photosynthetically active radiation. Birchler et al. (10) found that chlorophyll fluorescence of fertilized *Pseudotsuga menziesii* seedlings was constantly higher than that of unfertilized seedlings. Fertilization and light intensity interacted in their effect on SPAD readings. Low rates of photosynthesis and low capacity for energy dissipation predispose the photosynthetic apparatuses of shade-adapted plants to photoinhibition. Among plants fertigated 60 days at a moderate rate (75 mg·liter^{-1} N applied from August 1 through September 29), exposure to 100% *PPFD* from May 1 through September 30 followed by exposure to 50% *PPFD* increased SPAD readings in December, January, and February compared to other treatments grown under the same fertigation regime (Table 4). SPAD results indicate that plants acclimated to 100% *PPFD* conditions and experienced less chlorophyll damage in winter when light was reduced to 50% *PPFD.*

In a review of freeze protection practices, Rieger (32) concluded that once the chilling requirement has been met, phenological development of flower buds on fruit trees is related to the number of degree-hours that are accumulated. Reducing temperatures by sprinkling to promote evaporative cooling delayed anthesis of apples by up to 17 days (3), and peaches by up to 15 days (13). Radiative heating in high light increased plant tissue temperatures up to 15C (27F) above ambient air temperature on bright, clear winter days (22). In this study, we hypothesized that the heat load reductions associated with shade would delay anthesis. The average daily maximum temperature between January 1 and March 31, 2005, measured 18.2C (64.8F) in low light (50% *PPFD*) versus 21.4C (70.5F) in high light (100% *PPFD*) plots. Unlike temperature reductions associated with irrigation during the period of degree-hour accumulation, the lower temperatures associated in 50% *PPFD* plots failed to postpone azalea F_{50}, the date when 50% of flowers were in bloom (data not shown). The absence of an anthesis response to different light intensity treatments may be partially explained by Anisko et al. (5) who reported that azalea tissues deharden rapidly when exposed to warm air temperatures once chilling requirements have been satisfied.

Contrasting reports appear in the horticultural literature with regard to the effects of light intensity on the timing of azalea anthesis. *Rhododendron* ×*kurume* 'Coral Bells' that were grown outdoors and shaded by a lath bloomed before plants that were exposed to 100% *PPFD* (23). When 15 va-

Table 5. Effects of daily 0.5 liter fall fertigation and light intensity treatments on total mean number of flowers produced by *R.* ×*kurume* 'Pink Pearl'.

N fertilizer (mg·liter^{-1} N)		Light intensity (% *PPFD*)		
August 1 to September 29	September 30 to November 28	May 1 to September 30	October 1 to May 1	Total number of flowers
75	0	50	50	185a[zy]
75	0	50	100	142b
75	0	100	50	155b
75	0	100	100	129b
125	125	50	50	235a
125	125	50	100	177b
125	125	100	50	97c
125	125	100	100	140cb

[z]Each mean based on observations of five plants in each of three replicates.

[y]Means separated by Tukey's Studentized range test at $P \leq 0.05$.

rieties of azaleas were grown under greenhouse conditions, the average bloom date was 1 day later for plants grown in 50% *PPFD* compared to 100% *PPFD* (38).

In contrast with the absence of a response to light intensity treatments, azalea anthesis was affected by fall fertilization. Azaleas that received the high rate of extended fertilization (125 mg·liter^{-1} N from August 1 through November 28) bloomed nearly 5 days earlier (Day 96.3) than plants that received moderate fertilization (Day 101.2 for the treatment 75 mg·liter^{-1} N from August 1 through September 29). Previous studies reported that *Ilex crenata* 'Helleri' and *Ilex cornuta* 'Burfordi' (16), *Juniperus chinensis* 'Pfitzeriana'(8), and conifer seedlings (6, 7, 41) with high tissue nutrient content in fall begin growth earlier the next spring.

An interaction between fertigation and light treatments affected flower production (Table 5). However, regardless of the fertilizer treatment, plants that were grown in 50% *PPFD* throughout the study produced more flowers compared to other light treatments. These results were similar to those of Sweet (39), who found that flower production of 'Hinodegiri', 'Snow', and 'Formosa' azaleas increased when light intensity was reduced.

Table 6. Effect of light intensity treatments on leaf, stem and total above ground dry weight of R. ×*kurume* 'Pink Pearl' plants.

Light intensity (% PPFD)		Dry weight (g)		
May 1 to September 30	October 1 to May 1	Leaf	Stem	Shoot
50	50	21.3a[z,y]	18.4a	39.7a
50	100	19.1a	17.1a	36.3a
100	50	10.0b	4.8b	14.5b
100	100	9.7b	4.3b	14.4b

[z]In the absence of interaction, two fertilization treatments were pooled within each light intensity treatment, so that each mean is based on observations of five plants in each of three replicates.

[y]Mean separation within columns by Tukey's Studentized range test at $P \leq 0.05$.

Shoot dry weights of plants that received 60 days of extended fall fertigation at a moderate rate and those that received 120 days of extended fertigation at the high rate were similar (data not shown). Regardless of the fertilization treatment, leaf, stem and total shoot weight were higher among azaleas that were grown in 50% *PPFD* from May 1 through September 30 than among plants grown in 100% *PPFD* during the same time period (Table 6). Anderson et al. (4) grew *Rhododendron* × 'Pink Ruffles' under three light intensities and found that plants grown in 29% PPFD had less photoinhibition, less photooxidation, and more root and shoot growth than plants grown in 100% *PPFD*.

This study provides additional data to support the conclusion that high rates of extended fall fertilization should be discouraged. High rates of extended fall fertilization reduced stem freeze resistance and promoted early anthesis without increasing dry weight (data not shown). Shade treatments lacked a biologically significant impact on azalea cold hardiness or the timing of flower anthesis, but the application of shade fabric moderated air temperatures, reduced photosynthetic damage and promoted increases in azalea dry weight, and flower production. Reports of reduced freeze damage on plants grown in shaded versus exposed sites were likely caused by indirect effects of the shade canopy on freeze desiccation, air temperature, or photosynthetic damage rather than a direct effect on freeze resistance. Chlorophyll fluorescence was unrelated to stem freeze resistance and lacked usefulness as a predictor of stem LT_{50}.

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