Growth, Flowering, and Postharvest Performance of Single-stemmed Rose (*Rosa hybrida* L.) Plants in Response to Light Quantum Integral and Plant Population Density

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ABSTRACT. The cut rose, grown as a single-stemmed crop, resembles a potted plant and can be adapted to transportable bench systems. Potentially, this cultivation method could increase control of rose development, flexibility of production and produce, and automation of difficult or laborious cultural operations. Synchronous growth and flowering is considered important. The effects of increased quantum irradiation integral and plant density on shoot growth, fresh biomass production, and bloom quality were studied as single-stemmed rose plants (*Rosa hybrida* L.) ‘Kordapa’ Lambada, ‘Tanettahn’ Manhattan Blue, ‘Tanorelav’ Red Velvet, and ‘Sweet Promise’ Sonia grown under 20 hours photoperiods at 23 °C average air temperature. Plants were grown in rockwool cubes on ebb and flood benches irrigated with a complete nutrient solution, and were supplied with carbon dioxide at 1000 $\mu\text{mol}\cdot\text{mol}^{-1}$. Increased the daily quantum integral from 17.8 to 21.0 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ increased fresh biomass efficiency, stem diameter, and specific fresh mass while number of nodes, number of five-leaflet-leaves, plastochron value, and stem length at anthesis decreased. Fresh mass at anthesis was not affected by the treatments. Increasing plant population density from 100 to 178 plants/ m^2 increased stem length at visible flower bud, and reduced both fresh biomass efficiency and specific fresh mass. These effects are suggested to be related to assimilate supply and translocation, and light perception of the roses. High quantum integral slightly reduced flower diameter but in general, quantum integral or plant density did not affect bloom quality or vase life. Use of preservative floral solution generally improved rose flower diameter and vase life. In Lambada increased light quantum integral prolonged vase life, but use of preservative solution did not. The cultivars Sonia and Red Velvet required 19 to 20 days from cutting/planting until onset of bud growth, 29 to 34 days until visible flower bud, and 39 to 49 days until anthesis. Red Velvet roses were ≈ 60 cm long at anthesis, and had larger stem diameter and growth rate, accumulated more fresh biomass, were most efficient producing fresh biomass, and had higher specific fresh mass among the cultivars. Light quantum integral is suggested to be used as a means to synchronize single-stemmed rose plant development.

Due to the increasing production costs in Western Europe, North America, and Japan it is necessary to make rose harvest and other cultural practices more efficient by increased automation (Anderson, 1990; van den Berg, 1996; van Weel, 1996). This requires uniformity of axillary bud growth, flower initiation, and flower stem growth (Bredmose and Hansen, 1996a; Zieslin, 1996). In addition to engineering and logistic aspects (van Weel, 1996), research includes investigation of endogenous and exogenous factors involved in regulation of physiological processes in rose plants, and development of plants with an architecture suitable for automatic handling (Bredmose and Hansen, 1996b; Zieslin, 1996).

Alternatives to multi-stemmed greenhouse grown roses are the self-rooted, single-stemmed plants raised from single-node cuttings (Anderson, 1990; Bredmose and Hansen, 1996b; de Vries et al., 1977; Stoltz and Anderson, 1988), which may produce large numbers of uniform shoots per unit area in short cultivation cycles (Anderson, 1990; Bredmose and Hansen, 1996a; van Weel, 1996).

Inhibitory effects of one dominant shoot or bud upon one or more subordinate shoots or buds in a rose bush are absent in single-stemmed roses, enabling improved control of growth, development, and flowering of the single apical bud (Bredmose and Hansen, 1996a). This makes automation of cut rose production possible by means of robotic handling and harvest (Bredmose and Hansen, 1996b), and advance flexibility of production and produce.

The irradiation quantity received potently affects rose plant development and growth as reviewed by Zieslin and Mor (1990). Rose plant light saturation takes place at a photosynthetic photon flux (PPF) of $\approx 1000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at both ambient and elevated CO_2 concentrations (Baille et al., 1996; Jiao et al., 1991), and at least 20 h photoperiod is beneficial for rose growth (Bredmose, 1993; Jiao et al., 1991). Consequently, most European glasshouse-grown roses would benefit from supplemental PPF (Bredmose, 1997).

Increasing PPF reduces abortion of flower organs, especially at early flower development stages (Bredmose, 1997; Mass et al., 1995; Nell and Rasmussen, 1979). Increased PPF reduced the development time of roses (Moe, 1972), and quantitative relationships between total PPF and rose crop timing has been reported (Bredmose, 1997). These effects may be related to rose assimilate supply and PPF perception (Bredmose, 1997; Halevy, 1996; Marcelis van Acker, 1994).

Increasing PPF during rose culture may reduce cut rose vase life due to increased transpiration rate caused by incomplete closing of stomata at night (Slootweg and van Meeteren, 1991) or improve

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vase life by increasing level of accumulated carbohydrate (Fjeld et al., 1994).

Plant population density affects PPF interception per plant similar to variable PPF integrals. Developmental and allocation patterns often are affected by plant population density, by influencing photomorphogenic mechanisms involved in the allocation responses for many plant species (Ballaré et al., 1995). For roses, higher plant density increases leaf area index, plant height, plant mass/m², number of flowers/m², and plant mortality, but higher density decreases individual plant mass, stem diameter, and first grade bloom quality (de Vries and Dubois, 1988; Kool, 1997).

Bredmose and Hansen (1996a, 1996b) suggested that topophysis, the effect on growth and differentiation of position of axillary buds along the shoot, is a decisive tool for synchronization of development and flowering in roses, since their results show that rose plant growth potential, growth efficiency, and plant quality can be improved by 49%, 14% to 34%, and 20%, respectively, by selecting proper bud and cutting positions. Temperature and PPF (Hopper and Hammer, 1991) are two other such tools.

Variable growth and flowering were examined in response to various levels of PPF and plant density over three physiological developmental phases (Fig. 1) for single-stemmed rose plants. The objective of this study was to quantify the relationships between both PPF daily integral and plant population density with axillary bud growth, shoot elongation, fresh biomass formation, flowering, and post production quality of four cultivars of single-stemmed grown rose plants in search for methods to synchronize plant growth with flowering.

Materials and Methods

PLANT MATERIAL, GROWTH, AND FLOWERING.

The cultivars used were *Rosa hybrida* L. 'Kordapa' Lambada, 'Tanettahn' Manhattan Blue, 'Tanorelav' Red Velvet, and 'Sweet Promise' Sonia. Multi-stemmed 16-month-old stock plants, grown at 16 plants/m² of bed, were pruned above three to four five-leaflet-leaves and weak shoots were removed. The stock plants were grown in rockwool slabs at an average air temperature of 21.8 ± 1.1 °C and an average PPF of 183 μmol·m⁻²·s⁻¹. Other conditions were as reported by Bredmose and Hansen (1996a).

From subsequently developing first grade flowering shoots, at the stage when two sepals were separated from the petals, single-node cuttings with one five-leaflet-leaf and one axillary bud were taken (cutting and excision) from position four to six from apex, to avoid topophytic effects (Bredmose and Hansen, 1996a). Cuttings were taken 0.5 to 1.0 cm above and 4.0 to 5.0 cm below the node. Average stem diameter and fresh mass of cuttings were 0.48 cm and 2.0 g, respectively. Cuttings were planted on the same day in week 13 of 1995, dipped in 0.15% Captan-solution, and the basal end was treated with 0.3% indolebutyric acid before insertion 2 cm into rockwool cubes (7.5 × 7.5 × 6.5 cm, type

DU4G, Grodania A/S, Hedehusene, Denmark). All cuttings were rooted under a polyethylene cover in a glasshouse and grown as single-stemmed plants, and were acclimatized by gradually removing the polyethylene cover at end of rooting period.

Average growth medium and air temperatures during plant growth and flowering was 23.6 and 24.0 °C, respectively, with the time course shown in Fig. 1. Plants were ebb and flood irrigated with a complete nutrient solution (Bredmose and Hansen, 1996a) whenever 1 mm water had evaporated from an evaporative pan. Carbon dioxide was supplied at 1000 μmol·mol⁻¹ during the whole

Fig. 1. Time course of average daily air temperature, measured at canopy level, and root temperature, measured in rockwool cubes (above), and time course of the average (ambient plus supplementary) daily photosynthetic photon flux (PPF), measured inside the glasshouse at canopy level for high (21.0 mol·m⁻²·d⁻¹) or low (17.8 mol·m⁻²·d⁻¹) average daily PPF quantum integrals (below) during the experimental period 30 Mar. to 1 June, 1995. Arrows indicate average date to reach stages of development.

photoperiod except during ventilation which took place at temperatures ≥ 26 °C. Temperature and PPF measured each minute using a data logger (Datataker 600, DT600, Data Electronics (Austr.) Pty Ltd, Rowville, Australia) were averaged hourly and recorded in data files.

TREATMENTS. Plants were placed at two population densities, 100 or 178 plants/m² of bench area, 10 respective 7.5 cm apart. Whenever the natural PPF inside the glasshouse fell below 85 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ two levels of supplemental PPF were provided for up to 20 h·d⁻¹ by 400-W high-pressure sodium lamps (SON-T 400/SGR 200, Philips, Eindhoven, The Netherlands). The 4 h of darkness began at sunset, and the start of this period was adjusted weekly to follow natural time for sunset. PPF was measured at canopy level using an OL-2000Q quantum sensor (Optisk Laboratorium ATV, Lyngby, Denmark) with US NBS calibration. Supplemental PPF treatments produced a total (ambient + supplementary) average PPF inside the glasshouse of 248 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (low) or 292 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (high) (Fig. 1). These treatments gave average daily PPF integrals of 17.8 or 21.0 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ during the experimental period from 30 March to 1 June, 1995. The difference between the two PPF treatments varied during the experiment, and became smaller toward the end of the experiment (Fig. 1), due to enhanced shading from lamps at high levels and a naturally decreasing demand for working hours of the supplementary lighting system.

POSTHARVEST PROCEDURE. The effect of preharvest treatments on cut rose bloom postharvest performance was studied after overnight wet storage standing in a sugar-lacking preservative solution (RVB, 10 mL·L⁻¹; Pokon & Chrysal, Naarden, The Netherlands) at ≈ 3 °C air temperature, recutting, and defoliation of lower ≈ 20 cm stem. Ten stems per plot were placed individually in glass tubes (length $\times$ diameter = 19.8 $\times$ 3.2 cm; Schott, Duran, Germany) containing either tap water or tap water plus a floral preservative at recommended rate (Chrysal, 15 g·L⁻¹; Pokon & Chrysal BV). The glass tubes were kept in racks placed in a controlled environment room (CER) for cut flower post production evaluation. Solutions were refilled and longevity was measured daily. CER conditions were 20 °C air temperature, $\approx 60\%$ relative humidity, 12-h photoperiod, PPF at bud level 30 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (fluorescent tubes; Philips type TLD 58W/84), and air change ≈ 0.3 volume per hour. Vase life was considered terminated, and plants were removed, when leaves, petals, or stems lost $>50\%$ of their turgidity or color.

RECORDINGS. Measurements on each plant were made daily. During root formation and plant growth, dead or non-rooted plants were noted. During plant growth, the number of blind shoots were recorded. For rooted plants, the number of days from cutting and

planting until onset of bud growth, (defined by a shoot length ≥ 0.5 cm) and the number of days until visible flower bud (VFB) were recorded. At the stage of VFB, shoot length and total number of nodes (including nodes with greater than or equal to five-, three-, or one-leaflet-leaves, scales and also including those with nonelongated internodes) were recorded. Number of days from cutting and planting until anthesis (defined by the stage when two sepals were separated from the petals) was recorded. At anthesis, stem length (from the stem base to uppermost flower part), flower height (defined as height of bloom from uppermost stem end), stem diameter (3 cm above base), and fresh mass were measured, the number of five-leaflet-leaves were recorded, and bloom quality (color, abundance, shapeliness; scale 1 to 5 = best) was evaluated.

A plastochron was defined as the average number of days for a node to develop (days from cutting and planting to VFB divided by total number of nodes). Average internode length was measured as stem length at anthesis divided by total number of nodes. Average growth rate was calculated as stem length at anthesis divided by number of days until anthesis. Average fresh biomass efficiency was defined as the fresh mass at anthesis divided by the number of days to anthesis. Specific fresh mass was defined as the average fresh mass per unit length of stem (fresh mass at anthesis divided by stem length at anthesis). Postharvest studies of the cut roses included measurements of longevity (days from end of storage until vase life termination), and flower unfolding ability (defined as flower diameter measured at the petals fully reflexed stage).

EXPERIMENTAL DESIGN AND STATISTICS. The experiment was a split-plot design arranged in a two PPF daily integrals $\times$ two plant population densities (main plot) factorial combination for four cultivars (subplot) with 16 plants in each treatment combination and two replications. Treatment plots were randomized within each replication and surrounded by guard-row plants. The postharvest experiment was a split-split plot design with vase solution as main plot, PPF daily integral $\times$ plant density as subplot, and cultivar as subsubplot. Treatment subplots were randomized within main plots. Data were analyzed by means of analysis of variance using the General Linear Models procedure (SAS Institute, Cary, N.C.). The estimates pairwise comparison was made by *t* tests at *P* = 0.05.

Results

There were no significant interactions between PPF quantum integral or plant population density and cultivar, except for fresh biomass efficiency, flower height at anthesis, and vase life. Therefore, generally average results of the four cultivars are presented. Further, generally no interactions between PPF integral and plant

Table 1. Stem length and total node number at visible flower bud, and stem length, internode length, five-leaflet-leaf number, and flower height at anthesis of single-stemmed cut roses (average of four cultivars—Lambada, Manhattan Blue, Red Velvet, and Sonia, two replications, and two plant densities or PPF integrals, respectively) grown at either low (17.8) or high (21.0 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) daily PPF integral and low (100) or high (178 plants/m²) plant population density.

Treatment	At visible flower bud		At anthesis			
	Stem length (cm)	Total nodes (no.)	Stem length (cm)	Internode length (cm)	Five-leaflet leaves (no.)	Flower ht (cm)
PPF integral ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)						
17.8	26.8 a ²	13.1 b	45.1 b	3.44 a	8.28 b	3.57 a
21.0	25.4 a	12.8 a	42.6 a	3.32 a	7.82 a	3.52 a
Plant population density (plants/m ²)						
100	25.1 a	12.9 a	43.0 a	3.34 a	7.94 a	3.55 a
178	27.3 b	13.1 a	44.8 a	3.44 a	8.17 a	3.53 a

²Numbers within the same column and section followed by the same letter are not significantly different at *P* = 0.05.

Table 2. Stem diameter and fresh mass accumulated at anthesis, and growth rate, fresh biomass efficiency, and specific fresh mass of single-stemmed cut roses (average of four cultivars—Lambada, Manhattan Blue, Red Velvet, and Sonia, two replications, and two plant densities, or two PPF integrals, respectively) grown at either low (17.8) or high (21.0 mol·m⁻²·d⁻¹) daily PPF integral and low (100) or high (178 plants/m²) plant population density.

Treatment	Stem diam at anthesis (mm)	Stem growth rate (mm·d ⁻¹)	Fresh mass accumulation at anthesis (g/bloom)	Fresh biomass efficiency (g·d ⁻¹)	Specific fresh mass (g·m ⁻¹)
PPF integral (mol·m ⁻² ·d ⁻¹)					
17.8	4.46 a ^z	9.25 a	19.2 a	0.392 a	41.7 a
21.0	4.58 b	9.57 a	19.0 a	0.427 b	43.7 b
Plant population density (plants/m ²)					
100	4.53 a	9.45 a	19.5 a	0.426 b	44.3 b
178	4.50 a	9.38 a	18.7 a	0.390 a	40.8 a

^zNumbers within the same column and section followed by the same letter are not significantly different at $P = 0.05$.

density were found for the environmental factors (Tables 1–3).

High PPF integral resulted in plants with slightly reduced node numbers, 5.6% less five-leaflet-leaves, and 5.5% reduced stem length at anthesis, but high PPF integral did not significantly reduce stem length at VFB stage (Table 1). This corresponds with bud growth stage occurring $\approx 5\%$ earlier and shoot development until VFB and anthesis being $\approx 11\%$ quicker in plants at high light integral or low plant density (Bredmose, 1997). The plastochron value was significantly ($P < 0.05$) lower at flowering for high PPF integral, 2.7 d/node compared with 2.8 d/node at low light integral. In the denser planting, stem length was 8.7% greater at VFB, but this difference was not evident at anthesis (Table 1). Internode length and flower height were not significantly influenced by the

treatments, and plant density did not significantly affect total node number or the number of five-leaflet-leaves (Table 1).

Fresh biomass efficiency was increased by 8.9% or 8.5%, and specific fresh mass by 4.8% or 7.9% in plants at high PPF integral or low plant density, compared to the reverse (Table 2). High PPF integral increased stem diameter slightly. Growth rate and fresh mass accumulation was not significantly affected by the treatments, and plant density did not significantly influence stem diameter (Table 2). There was an interaction ($P < 0.05$) of PPF integral and plant population density with cultivar on specific fresh mass (Fig. 2). As the PPF integral decreased and plant density increased the specific fresh mass of Lambada and Sonia slightly was reduced (Fig. 2). However, for Manhattan Blue a reduction in

Table 3. Postharvest performance (flower diameter, vase life, and bloom quality) of single-stemmed cut roses (average of four cultivars—Lambada, Manhattan Blue, Red Velvet, and Sonia, two replications, and two plant densities or two PPF integrals, respectively) grown preharvest at either low (17.8) or high (21.0 mol·m⁻²·d⁻¹) daily PPF integral and at low (100) or high (178 plants/m²) plant population density. Postharvest preservative solution data are average of PPF, density, and cultivar, and cultivar data are average of PPF, density, and solution.

Treatment	Flower diam, petals reflexed (cm)	Vase life (d)	Bloom quality evaluation (1–5 = best)
PPF integral (mol·m ⁻² ·d ⁻¹)			
17.8	8.9 b ^z	9.5 a	4.7 a
21.0	8.6 a	9.1 a	4.7 a
Plant population density (plants/m ²)			
100	8.8 a	9.2 a	4.7 a
178	8.7 a	9.4 a	4.7 a
Preservative solution			
Tap water, control	7.9 a	7.0 a	NE ^y
Crysal, 15 g·L ⁻¹	8.9 b	11.6 b	NE
Cultivar			
Lambada	8.2 b	13.9 c	4.9 b
Manhattan Blue	7.8 a	6.7 a	4.8 b
Red Velvet	9.9 d	10.3 b	4.9 b
Sonia	9.6 c	6.3 a	4.2 a
Significance			
Quantum integral (QI)	*	NS	NS
Plant density (PD)	NS	NS	NS
QI × PD	NS	NS	NS
Preservative solution (PS)	*	**	NE
Cultivar (C)	*	***	***
QI × C	NS	*	NS
PS × C	*	**	NE

^zNumbers within the same column and section followed by the same letter are not significantly different at $P = 0.05$.

^yNE = not evaluated.

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

Fig. 2. Specific fresh mass (quality index; $\text{g}\cdot\text{cm}^{-1}$) for four combinations of PPF quantum integral ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) and plant population density ($\text{plants}\cdot\text{m}^{-2}$) for plants of four cultivars of single-stemmed roses. Different letters on columns indicate significant mean separation at $P=0.05$.

specific fresh mass was mainly at low PPF integral and high plant density, while Red Velvet had high specific fresh mass at low PPF integral/high plant density, besides producing the highest specific fresh mass at high PPF integral and low plant density (Fig. 2).

There was an interaction ($P<0.05$) of PPF integral with cultivar on flower height at anthesis (Fig. 3). High PPF integral reduced flower height of Lambada, Red Velvet and Sonia, whereas it slightly enhanced the flower height of Manhattan Blue (Fig. 3). High PPF integral caused a slight ($\approx 3\%$) reduction in flower diameter at the petals reflexed stage, but in general the PPF integral or plant density treatments did not significantly affect bloom quality or vase life (Table 3). However, an interactive effect ($P<0.05$) of PPF quantum integral and cultivar on vase life showed reductive influence of high PPF integral especially in Red Velvet, whereas for Lambada a promotive effect was seen (Fig. 4). The use of a preservative vase solution generally improved rose flower diameter by 12% and vase life by 66% (Table 3). An interaction between preservative solution and cultivar on flower diameter ($P<0.05$) showed increased effect (from 7.9 to 8.3 cm) of using a preservative solution on Lambada flower diameter, while it decreased that of Manhattan Blue (from 8.4 to 7.7 cm). Cut flowers of Lambada and Red Velvet, respectively, kept longest (≈ 14 d) and developed the largest flowers (≈ 9.9 cm), while Sonia bloom quality was evaluated lowest (Table 3). An interaction ($P<0.01$) between preservative solution and cultivar showed no effect of the preservative solution on Lambada vase life, while vase life was doubled for the other three cultivars (from ≈ 4 to 7 to ≈ 9 to 14 d).

Regardless of treatments plants of Sonia and Red Velvet developed faster than plants of Manhattan Blue and Lambada. The former required 19 to 20 d from cutting until onset of bud growth, 29 to 34 d until VFB, and 39 to 49 d until anthesis, and plants used 2.3 to 2.6 d to develop a node (Table 4). Red Velvet developed the longest stems, the longest internodes, and the tallest flower (Table 5). Lambada and Red Velvet had the largest number of nodes and five-leaflet-leaves (Table 5). Red Velvet had a greater stem diam-

eter and a higher growth rate, accumulated more fresh mass, was the most efficient producer of fresh biomass (Table 6), and had a higher specific fresh mass than the other three cultivars (Fig. 2; Table 6).

Discussion

Analogous to single-stemmed roses, adapting single-truss tomato crop to transportable table system increases potential for automation for a labor intensive crop (Chiu et al., 1996; McAvoy and Giacomelli, 1986). Potential advantages are optimal use of glasshouse space and supplemental PPF, improved environmental and ecological control, and computer assisted management. For both crops, synchronization of plant development is important, retaining plant growth efficiency and plant quality.

GROWTH AND FLOWERING. Plant growth efficiency may be expressed by fresh biomass efficiency and plant quality by specific fresh

mass (Bredmose and Hansen, 1996a; Tsujita and Dutton, 1983). Fresh biomass efficiency and specific fresh mass was increased at high PPF integral and low plant density (Table 2), while, in accordance with observations of Blom-Zandstra et al. (1995), no significant difference in fresh mass at anthesis was found between plants grown at the two quantum integrals (Table 2). This suggests that increased PPF integral for single-stemmed roses mainly decreases plant developmental time and increases plant quality, and thus, are not necessarily just related to total biomass accumulation. These results correspond well with results showing advanced axillary bud growth and shoot development of rose plants at low plant density or high PPF integral (Bredmose, 1997; Hopper and Hammer, 1991). Similar to findings of Hopper and Hammer (1991), our results showed slightly increased stem diameter at anthesis (Table 2). In addition fewer five-leaflet-leaves occurred at

Fig. 3. Flower height at anthesis (cm) at high (21.0) or low (17.8) average daily PPF quantum integral for plants of four cultivars of single-stemmed roses.

Fig. 4. Vase life (d, averaged over treatments with preservative solution, and treatments with tap water) for cut flowers of plants of four cultivars of single-stemmed roses grown at high (21.0) or low (17.8 mol·m⁻²·d⁻¹) average daily PPF quantum integral.

high PPF integral (Table 1). Contrary to single-stemmed roses (Table 2), multi-stemmed rose plants had increased stem mass due to supplemental PPF (Bredmose, 1993; Hopper and Hammer, 1991; Tsujita and Dutton, 1983), most likely due to increase in leaf number (Bredmose, 1993). Generally, conditions that enhance carbohydrate levels promote rose flower bud development (Halevy, 1996).

Raising average daily PPF quantum integral from 17.8 to 21.0 mol·m⁻²·d⁻¹ approximately halved the percentage of blind shoots in roses (Bredmose, 1997), indicating that a critical PPF for completing

rose flower bud development is relatively high. PPF is used by plants as a source of both energy and informational signals. Plant population density influences PPF interception per plant and therefore source strength, as do different PPF quantum integrals, and plants can respond to density, before resources become depleted (Ballaré et al., 1995). A promotive effect of supplemental PPF on roses, which were characterized by an absence of foliage, has been reported (Carpenter and Rodriguez, 1971), and light perception by axillary buds or shoot tips of roses has been documented (Mor et al., 1980). Therefore, it has been suggested that a significant response to PPF on single-stemmed rose plant growth and development, even from cuttings, seems reasonable (Bredmose, 1997).

Although fresh mass accumulated per bloom was not significantly different at the two plant densities (Table 2), fresh mass per unit area obviously differed. Similarly, *R. canina* L. 'Inermis' seedling plant fresh biomass increased until 170 plants/m² (de Vries and Dubois, 1988). However, increasing the single-stemmed rose plant population density from 100 to 178 plants/m² the percentage of plants with successful bud growth decreased, and the percentage of plants with blind shoots and plants without bud growth increased (Bredmose, 1997). The results of longer stems (Table 1) and lower specific fresh mass (Table 2) at higher plant density are similar to other rose spacing results (de Vries and Dubois, 1988; Kool, 1997). According to Schwinning (1996), in dense plant stands resources can be divided between competitors in proportion to the biomass of competing individuals (symmetric competition), or so that large competitors get more than their proportional share (asymmetric competition). The observation of de Vries and Dubois (1988), that competition between rose shoots for PPF appears to be more intense than between roots for water and nutrition, is consistent with general findings that competition for soil resources is symmetric, whereas competition for PPF is asymmetric (Schwinning, 1996).

Rose shoot growth is mainly dependent on the assimilate supply available during growth, and developing flowers make intensive use of carbohydrates and other metabolites (Halevy, 1996; Marcelis-

Table 4. Cultivar effects (F probability ≤0.001 for all) on time to axillary bud growth, visible flower bud, and anthesis and on plastochron. Average of two PPF integrals, two plant densities, and two replications.

Cultivar	Time (d) from planting until			Plastochron (d/node)
	Axillary bud growth	Visible flower bud	Anthesis	
Lambada	22.9 c ²	36.9 c	47.8 b	2.52 b
Manhattan Blue	26.1 d	37.6 c	52.2 c	3.54 c
Red Velvet	20.1 b	34.1 b	48.6 b	2.29 a
Sonia	18.7 a	29.0 a	39.4 a	2.56 b

²Numbers within the same column followed by the same letter are not significantly different at *P* = 0.05.

Table 5. Cultivar effects (F probability ≤0.001 for all) on total number of nodes at visible flower bud, stem length at visible flower bud, and at anthesis, and on length of internode, number of five-leaflet-leaves, and flower height at anthesis. Average of two PPF integrals, two plant densities, and two replications.

Cultivar	At visible flower bud		At anthesis			
	Stem length (cm)	Total nodes (no.)	Stem length (cm)	Internode length (cm)	Five-leaflet leaves (no.)	Flower ht (cm)
Lambada	28.0 b ²	14.7 c	41.8 b	2.84 a	10.19 ^d	3.05 a
Manhattan Blue	21.0 a	10.8 a	36.2 a	3.38 b	6.78 b	3.57 c
Red Velvet	35.3 c	15.0 c	59.4 c	3.97 c	9.70 c	4.33d
Sonia	20.2 a	11.4 b	38.1 a	3.35 b	5.50 a	3.23 b

²Numbers within the same column followed by the same letter are not significantly different at *P* = 0.05.

Table 6. Cultivar effects (F probability ≤ 0.001 for all) on stem diameter and fresh mass accumulation at anthesis, growth rate, fresh biomass efficiency, and specific fresh mass. Average of two PPF integrals, two plant densities, and two replications.

Cultivar	Stem diam at anthesis (mm)	Stem growth rate (mm·d ⁻¹)	Fresh mass accumulation at anthesis (g/bloom)	Fresh biomass efficiency (g·d ⁻¹)	Specific fresh mass (g·m ⁻¹)
Lambada	4.40 c ²	8.78 b	15.7 b	0.332 a	37.5 a
Manhattan Blue	4.12 b	6.99 a	16.5 b	0.322 a	45.9 b
Red Velvet	5.63 d	12.26 d	30.5 c	0.632 c	51.0 c
Sonia	3.94 a	9.70 c	14.0 a	0.360 b	36.8 a

²Numbers within the same column followed by the same letter are not significantly different at $P = 0.05$.

van Acker, 1994). Mor et al. (1980) showed that PPF received by the rose shoot tip promoted shoot sink activity by increasing the sucrose unloading process. Therefore, it is suggested that by applying different light quantum integrals or plant population densities, assimilate supply and translocation can be adjusted, thereby the rate of bud and shoot growth, and the quality of the stem and flower can be influenced, for single-stemmed rose plants.

POSTHARVEST PERFORMANCE. After harvest, cut roses experience PPF conditions below the light compensation point of ≈ 30 to $70 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ (Zieslin and Mor, 1990). Rose bloom growth and development, therefore, depends on the presence of adequate levels of storage carbohydrates in the corolla, on a supply from stem and leaves, and ultimately on exogenously supplied sucrose (Evans and Reid, 1988; Kuiper et al., 1995; van Doorn et al., 1991). PPF integral or plant density generally did not affect vase life or bloom quality, but at high PPF integral a reduction in flower diameter was observed (Table 3). These results are consistent with findings of Armitage and Tsujita (1979), Blom-Zandstra et al. (1995), and Zieslin and Mor (1990), that supplemental PPF had no effects on vase life of cut roses, but they are in contrast to positive effects reported by Fjeld et al. (1994). These differential responses to PPF integral and carbohydrate indicate interactions with other factors involved in controlling rose vase life. Blom-Zandstra et al. (1995) found that stomatal closure rate depends on duration of photoperiod and might be affected by endogenous factors.

Due to occlusion caused by bacteria at the cut surface, bacteria in xylem, and cavitation in xylem cut rose flower vase life in tap water often is reduced (van Doorn and de Witte, 1997). Preservative solutions containing bactericide, acidifier and sucrose improves rose vase life (Marousky, 1971). Use of preservative vase solution markedly improved rose flower unfolding ability (flower diameter) and the vase life of the roses (Table 3). It is well known that adding sucrose to vase solution improves color, flower diameter and longevity of roses (Borochov et al., 1976; Durkin, 1979). Sugars may provide adenosine triphosphate for active transport of substances into expanding corolla tissue, and may contribute to decrease in osmotic potential driving cell elongation (van Doorn et al., 1991). As no cultivars have been bred for the single-stemmed cultivation method the observed differences in cultivar reaction on treatments (Figs. 2–4) and on the method (Tables 4–6) may indicate a potential.

About an 18% increase in daily PPF quantum integral increased growth efficiency (developmental time by 9% (Bredmose, 1997), fresh mass efficiency by 9%), and plant quality (specific fresh mass by 5%, flower stem diameter by 3%) of the roses. Further, increased PPF integral reduced five-leaflet-leaf number, stem length by 5%, and slightly reduced node number and flower diameter. Thus, PPF integral may be a suitable tool to use to control single-stemmed rose plant growth and bloom quality for the purpose of synchronizing development.

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