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Regression Models Describing *Rosa hybrida* Response to Day/Night Temperature and Photosynthetic Photon Flux

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Abstract. A central composite rotatable design was used to estimate quadratic equations describing the relationship of irradiance, as measured by photosynthetic photon flux (PPF), and day (DT) and night (NT) temperatures to the growth and development of *Rosa hybrida* L. in controlled environments. Plants were subjected to 15 treatment combinations of the PPF, DT, and NT according to the coding of the design matrix. Day and night length were each 12 hours. Environmental factor ranges were chosen to include conditions representative of winter and spring commercial greenhouse production environments in the Midwestern United States. After an initial hard pinch, 11 plant growth characteristics were measured every 10 days and at flowering. Four plant characteristics were recorded to describe flower bud development. Response surface equations were displayed as three-dimensional plots, with DT and NT as the base axes and the plant character on the z-axis while PPF was held constant. Response surfaces illustrated the plant response to interactions of DT and NT, while comparisons between plots at different PPF showed the overall effect of PPF. Canonical analysis of all regression models revealed the stationary point and general shape of the response surface. All stationary points of the significant models were located outside the original design space, and all but one surface was a saddle shape. Both the plots and analysis showed greater stem diameter, as well as higher fresh and dry weights of stems, leaves, and flower buds to occur at flowering under combinations of low DT (≤ 17C) and low NT (≤ 14C). However, low DT and NT delayed both visible bud formation and development to flowering. Increased PPF increased overall flower stem quality by increasing stem diameter and the fresh and dry weights of all plant parts at flowering, as well as decreased time until visible bud formation and flowering. These results summarize measured development at flowering when the environment was kept constant throughout the entire plant growth cycle.

Growth and development of the greenhouse rose are strongly influenced by irradiance and temperature. Studies in the greenhouse (Armitage and Tsujita, 1979a, 1979b; Tsujita, 1982) and in growth chambers (Butt and Tsujita, 1986) have illustrated that flower weight increases with increasing irradiance. Yield, as flowers per square meter, also increases as irradiance increases either naturally (Post and Howland, 1946; Mattson and Widmer, 1971) or with artificial supplementation (Carpenter and Anderson, 1972; Cockshull, 1975; White and Richter, 1973). PPF, those wavelengths of radiation in the 400- to 700-nm band, have been shown to have the most direct influence on plant growth (Savage, 1982). Daily supplementation with as low as 65 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 12 h increased yield and quality while decreasing flowering time by 1 to 2 days during a period of five winter months from October to March (Tsujita, 1982). Supplementation with 158 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 12 h more than doubled the yield over nonirradiated control plants while reducing flowering time by 4 to 5 days over the 4 months from October to January (Armitage and Tsujita, 1978a).

Temperature has been shown to influence rate of plant development and flower quality. Low temperatures (10-12C) delayed development for some cultivars (DeVries et al., 1986; Hanan, 1979) and resulted in higher incidence of both blind shoots (bud atrophy) and “bullhead” development (malformed flowers) (Hanan, 1979; Moe, 1971). The interaction between PPF and temperature has been demonstrated to have a significant impact on rose growth (Holcomb and Arteca, 1987; Jaio et al., 1988).

Interactions between several independent environmental factors can be quantified using response surface methods (Myers, 1976). Previous plant growth studies have enlisted the central composite experimental design to produce a rigorous mathematical representation of response surfaces (Armitage et al., 1981; Hammer and Langhans, 1976; Heins et al., 1986; Kraszewski and Ormrod, 1986). A central composite rotatable design has the advantage of high efficiency when experimental units are homogeneous within a replication for a study of multiple factors, while rotatability allows uniform precision for predicted responses (Box and Draper, 1987; Box et al., 1978; Cochran and Cox, 1957; Kraszewski and Ormrod, 1986). The objective of this study was to use a central composite rotatable design to develop quadratic regression models for the response surfaces of several plant characteristics that reflect rose growth and development. Canonical analysis (Myers, 1976) facilitated simplified description of these surfaces and a better understanding of how plant response changes with movement on these surfaces within the original design space.

Materials and Methods

General methods

All treatments were conducted in Sherer Model CEC 512-37 controlled-environment chambers (Sherer-Gillett, Marshall, Mich.). The compartment dimensions were 2.6 × 1.34 × 1.6

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Abbreviations: DT, day temperature, NT, night temperature; PPF, photosynthetic photon flux.

m (length × width × height), creating an interior volume of 5.57m^3. The growth bench was 2.54 x 1.3 m.

PPF was generated using combinations of 28, 2.44-m-long, 215-W and eight, 1.22-m-long, 115-W Sylvania Very High Output cool-white fluorescent lamps and 12, 75-W Sylvania Super Saver incandescent lamps (Sylvania Lighting Corp., Danvers, Mass.). PPF was measured throughout each treatment period using a LI-COR LI-185 meter with a LI-COR LI-190S quantum (photon) sensor (LI-COR, Lincoln, Neb.). The sensor was placed on a level platform at the top of the plant canopy. There was no barrier between the lamps and plants. PPF was adjusted by altering the number of lamps and distance of the plants from the lamps.

Relative humidity (RH) was measured using a Bendix Model 566-3 Psychron aspirated psychrometer (Bendix Environmental Science Division, Baltimore). Flooding the plant compartment floor resulted in an RH of 50% to 95%. A Sherer Transistorized Electronic Dual Controller (Model-2-113) was adjusted to achieve desired set points for the day/night temperature regime of each treatment based on temperature readings from the aspirated psychrometer. Readings were taken every 7 to 14 days throughout the course of the treatment as a spot check to confirm integrity of the control system. A temperature probe in the chamber linked to the controller was shielded from direct radiation with aluminum foil.

Table 1. Selected levels of environmental factors and the set points established according to the desirer matrix.

Treatment no.	Coded axis[z]			Environmental set point		
				PPF	Temp (°C)	
	X_{PPF}	X_{DT}	X_{NT}	($\mu mol \cdot s^{-1} \cdot m^{-2}$)	Day	Night
1	−1.68	0	0	50	20	17
2	−1	−1	−1	100	17	14
3	−1	−1	1	100	17	20
4	−1	1	−1	100	23	14
5	−1	1	1	100	23	20
6	0	0	0	175	20	17
7	0	0	−1.68	175	20	12
8	0	0	1.68	175	20	22
9	0	1.68	0	175	25	17
10	0	−1.68	0	175	15	17
11	1	−1	1	250	17	20
12	1	1	1	250	23	20
13	1	−1	−1	250	17	14
14	1	1	−1	250	23	14
15	1.68	0	0	300	20	17

[z] Coded values from the design matrix for the central composite rotatable design.

Thirty-two XXX (highest grade) stock plants of 'Royalty' rose (E.G. Hill Co., Richmond, Ind.) were planted in 30-cm-diameter (15 liters) round plastic pots. The growing medium was 1 soil :2 sphagnum peat :2 perlite (by volume), pH 6.2, amended with the following nutrients (all per cubic meter): 744 g treble superphosphate, 496 g potassium nitrate, 496 g magnesium sulfate, 4 kg agricultural limestone, and 62 g Fritted Trace Element mix (Robert B. Peters Co., Allentown, Pa.). The plants were grown in a glass greenhouse with ambient irradiance and a 24/16C day/night cycle. Liquid fertilization with each irrigation provided 200 mg N/liter and 200 mg K/liter at pH 6.0 by injecting 75% (v/v) technical grade phosphoric acid into the system (29 mg P/liter). Periodic applications of monosodium ferric diethylenetriamine pentaacetate (Sequestrene 330) were made as a soil drench of 5.8 g/liter to prevent iron-deficiency chlorosis.

Plants used in the treatments were started as single-node cuttings from the stock plants. Cuttings were placed in a 6 sphagnum peat :4 perlite : 1 vermiculite (by volume) medium, pH 5.5, filling 6.5 × 9.0 × 6.O-cm single cells of 24 per 27 × 54 × 6.O-cm flat. Cutting size varied in stem diameter (0.5-1.2 cm), stem length (3.0-10.0 cm), and in leaf blade length (8.0-16.0 cm). The basal end of the cutting was dipped in a commercial, powdered preparation (Hormo-Root 2; Hortus Products Co., Newfoundland, N.J.) of 2% indole-3-butyric acid (IBA) before placement in the medium.

The cuttings were held under intermittent mist (4 sec every 4 min during daylight) for 4 weeks at a constant 21C and ambient irradiance. During the study, a commercial antifungal preparation of 1 bromo-3-chloro-5,5 dimethyl-2,4-imidazolidinedione (Agribrom; Great Lakes Chemical Corp., West Lafayette, Ind.) was added to the mist system via an injector; this

Table 2. Terms in five, full quadratic models of plant characteristics and model significance. The model form is: $y = b_o + b_1X_{PPF} + b_2X_{DT} + b_3X_{NT} + b_{11}X^2_{PPF} + b_{22}X^2_{DT} + b_{33}X^2_{NT} + b_{12}X_{PPF}X_{DT} + b_{13}X_{PPF}X_{NT} + b_{23}X_{DT}X_{NT}$.

Coefficient	Factor[z]	Characteristic									
				Fresh wt							
		Stem diam		Stem		Leaf		Flower		Total	
		Estimate	s_b	Estimate	s_b	Estimate	s_b	Estimate	s_b	Estimate	s_b
b_0	1	4.95	0.152	5.72	0.380	11.0	0.561	10.3	1.12	27.0	1.89
b_1	X_{PPF}	0.638	0.0926	1.68	0.231	2.73	0.341	2.44	0.680	6.84	1.15
b_2	X_{DT}	−0.313	0.0926	−1.08	0.231	−2.55	0.341	−2.06	0.680	−5.70	1.15
b_3	X_{NT}	−0.126	0.0926	−0.819	0.231	−1.28	0.341	−1.97	0.680	−4.07	1.15
b_{11}	$X_{PPF} \times X_{PPF}$	0.0181	0.0935	0.159	0.233	−0.0816	0.345	−0.756	0.687	−0.679	1.16
b_{12}	$X_{PPF} \times X_{DT}$	0.0841	0.121	−0.000988	0.301	−0.771	0.444	0.0562	0.885	−0.716	1.50
b_{22}	$X_{DT} \times X_{DT}$	0.0693	0.0935	0.0448	0.233	0.299	0.345	0.145	0.687	0.489	1.16
b_{13}	$X_{PPF} \times X_{NT}$	−0.0349	0.121	−0.162	0.301	−0.0712	0.444	0.0634	0.885	−0.170	1.50
b_{23}	$X_{DT} \times X_{NT}$	−0.211	0.121	−0.0475	0.301	0.0471	0.444	−0:280	0.885	−0.280	1.50
b_{33}	$X_{NT} \times X_{NT}$	0.027	0.0935	0.426	0.233	0.329	0.345	0.801	0.687	1.56	1.16
Significance	---	**		***		***		*		**	
R^2	---	0.879		0.910		0.939		0.789		0.893	

[z] As shown in the design matrix in Table 1. X_{PPF} = coded photosynthetic photon flux; X_{DT} = coded day temperature; X_{NT} = coded night temperature.

*,**,***Significantly different at P = 0.05, 0.01, or 0.001, respectively.

Table 3. Terms in four, full quadratic models and model significance for plant dry weight characteristics. The model form is: $y = b_0 + b_1 X_{PPF} + b_2 X_{DT} + b_3 X_{NT} + b_{11} X^2_{PPF} + b_{22} X^2_{DT} + b_{33} X^2_{NT} + b_{12} X_{PPF} X_{DT} + b_{3} X_{PPF} X_{NT} + b_{23} X_{DT} X_{NT}$.

		Characteristic							
		Dry wt							
		Stem		Leaf		Flower		Total	
Coefficient	Factor[z]	Estimate	s_b	Estimate	s_b	Estimate	s_b	Estimate	s_b
b_0	1	1.82	0.142	2.99	0.182	1.69	0.195	6.49	0.466
b_1	X_{PPF}	0.512	0.0866	0.785	0.111	0.338	0.119	1.64	0.283
b_2	X_{DT}	−0.363	0.0866	−0.647	0.111	−0.349	0.119	−1.36	0.283
b_3	X_{NT}	−0.301	0.0866	−0.475	0.111	−0.393	0.119	−1.17	0.283
b_{11}	$X_{PPF} \times X_{PPF}$	0.0171	0.0874	−0.0635	0.112	−0.120	0.120	−0.166	0.286
b_{12}	$X_{PPF} \times X_{DT}$	0.0242	0.113	−0.144	0.144	0.108	0.154	−0.0110	0.369
b_{22}	$X_{DT} \times X_{DT}$	−0.0153	0.0874	0.0330	0.112	0.00822	0.120	0.0260	0.286
b_{13}	$X_{PPF} \times X_{NT}$	−0.0700	0.113	−0.101	0.144	0.0281	0.154	−0.143	0.369
b_{23}	$X_{DT} \times X_{NT}$	0.0363	0.113	0.166	0.144	0.0622	0.154	0.265	0.369
b_{33}	$X_{NT} \times X_{NT}$	0.0823	0.0874	0.0358	0.112	0.149	0.120	0.267	0.286
Significance	---	**		***		*		**	
R^2	---	0.880		0.922		0.777		0.893	

[z] As shown in the design matrix in Table 1. X_{PPF} = coded photosynthetic photon flux; X_{DT} = coded day temperature; X_{NT} = coded night temperature.

*,**,*** Significantly different at $P = 0.05$, 0.01, or 0.001, respectively.

Table 4. Terms in four, full quadratic models for flower development and model significance. The model form is: $y = b_0 + b_1 X_{PPF} + b_2 X_{DT} + b_3 X_{NT} + b_{11} X^2_{PPF} + b_{22} X^2_{DT} + b_{33} X^2_{NT} + b_{12} X_{PPF} X_{DT} + b_{13} X_{PPF} X_{NT} + b_{23} X_{DT} X_{NT}$.

		Characteristic							
		Interval (days) to							
		Visible bud		First color		Sepal reflex		Flower	
Coefficient	Factor[z]	Estimate	s_b	Estimate	s_b	Estimate	s_b	Estimate	s_b
b_0	1	25.1	0.252	41.3	0.426	51.9	0.501	52.8	0.406
b_1	X_{PPF}	−1.40	0.153	−2.98	0.259	−3.12	0.305	−3.41	0.247
b_2	X_{DT}	−4.17	0.153	−5.57	0.259	−7.03	0.305	−8.24	0.247
b_3	X_{NT}	−2.90	0.153	−4.09	0.259	−4.99	0.305	−5.32	0.247
b_{11}	$X_{PPF} \times X_{PPF}$	0.248	0.155	0.740	0.262	−0.543	0.308	−0.319	0.249
b_{12}	$X_{PPF} \times X_{DT}$	0.238	0.199	0.450	0.337	0.425	0.397	0.575	0.322
b_{22}	$X_{DT} \times X_{DT}$	1.00	0.155	1.12	0.262	0.105	0.308	1.01	0.249
b_{13}	$X_{PPF} \times X_{NT}$	−0.238	0.199	−0.275	0.337	0.0750	0.397	0.325	0.322
b_{23}	$X_{DT} \times X_{NT}$	0.913	0.199	1.35	0.337	0.8750	0.397	0.725	0.322
b_{33}	$X_{NT} \times X_{NT}$	−0.274	0.155	−0.160	0.262	0.0332	0.308	−0.211	0.249
Significance	---	***		***		***		***	
R^2	---	0.993		0.990		0.990		0.995	

[z] As shown in the design matrix in Table 1. X_{PPF} = coded photosynthetic photon flux; X_{DT} = coded day temperature; X_{NT} = coded night temperature.

*,**,*** Significantly different at $P = 0.05$, 0.01, or 0.001, respectively.

prevented algae accumulation and improved overall cleanliness. After 4 weeks, the rooted cuttings were transplanted into 10-cm, square plastic pots (640 ml) of growing medium as was described for the stock plants, and mist was gradually reduced over 1 week before moving the plants to a growth chamber for treatment. Plants were acclimated to the growth chamber treatment conditions for 7 to 10 days before hard-pinching to leave two five-leaflet leaves on each new plant shoot. At the time of pinching, the 50 most uniform plants were selected for treatment, tagged, and randomized within the chamber.

Daylength was 12 h in all treatments. Day encompassed 1130 to 2330 HR for chamber 1 and 1200 to 2400 HR for chamber 2; this enabled convenient monitoring of day and night regimes. The 7- to 10-day adjustment period before pinch and start of the treatment allowed diurnal rhythms to adjust to the artificial daylength. Fertilizer was applied in daily irrigations with an automatic time-clock-regulated system. Two time clocks (24 h and 30 min) wired in series allowed 5 to 10 min of watering for a 15-min period each day, depending on plant age and water requirements. The clocks engaged a submersible pump that supplied nutrient solution from a 114-liter plastic reservoir through a spaghetti-tube, nonrecirculating irrigation system, with two lead-weighted tubes in each pot. Each liter of fertilizer solution supplied 250 mg each of nitrogen and potassium and other essential elements by including the following: 2.45 g $KN0_3$, 1.74 g NH_4N0_3, 0.02 g $MgS0_4$, 0.02 g Soluble Trace Element Mix (Robert B. Peters Co.), and 18.9 ml of 25 ml 75% technical grade H_3P0_4. Every 10 to 14 days, additional iron was supplied in the chelated form, Sequestrene 330, as a soil drench of 5.8 g·liter^{-1}.

Every 10 days, starting from the day of pinch, the growth from the topmost node was measured by destructive sampling of 10 plants until day 40 and at flowering. Additional shoots below the topmost node were removed after 10 days from pinch. Plant characteristics measured included number of nodes (NN), stem diameter, stem length, fresh weights of stem, leaves, and flower bud, as well as dry weights of stem, leaves, and flower

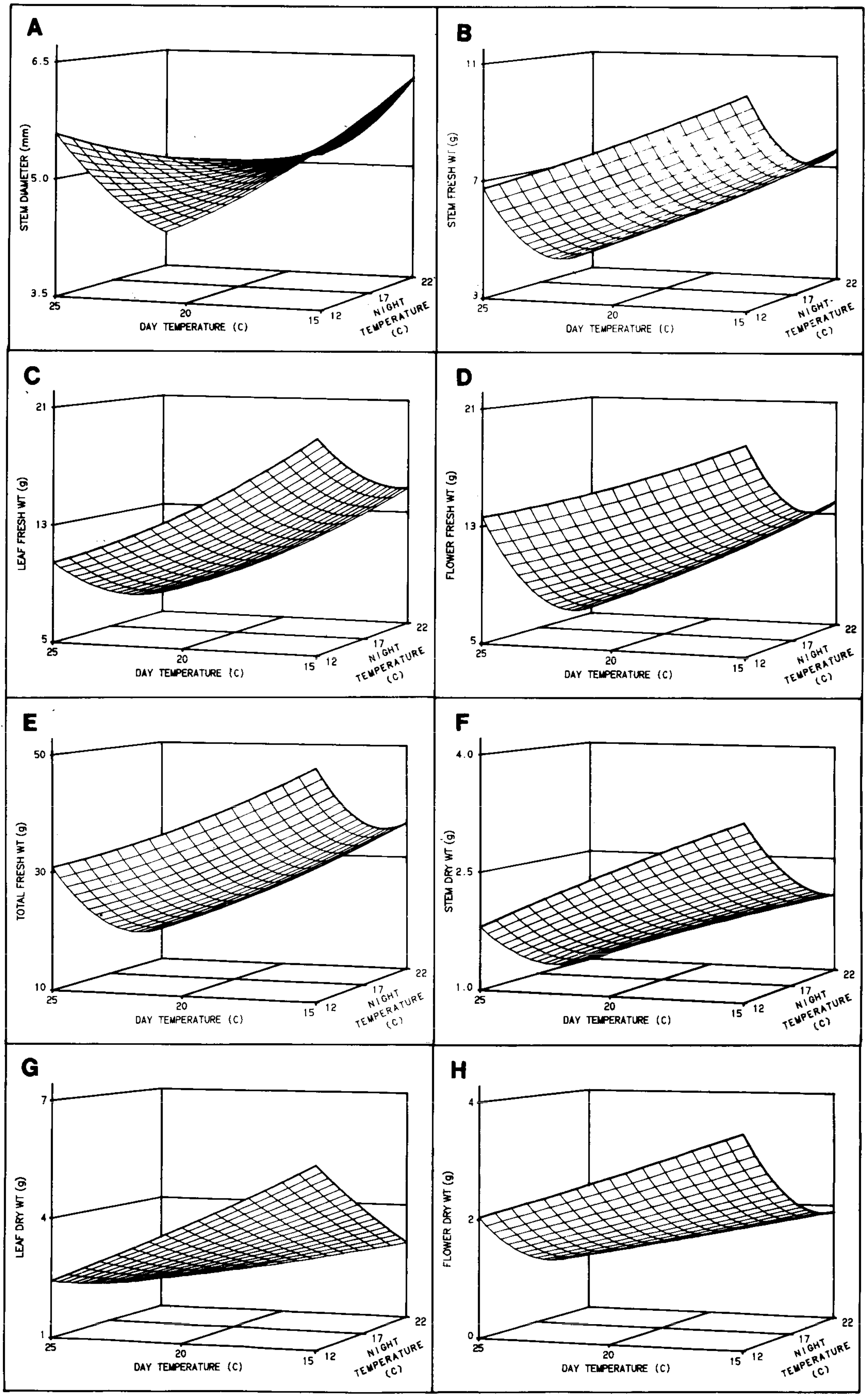

Fig. 1. Response surfaces for significant response characteristics of *Rosa hybrida* at flowering under constant controlled environments. Plots made for PPF = 175 µmol·m^{-2}·s^{-1} **(A)** Stem diameter, **(B)** stem fresh weight, (C) leaf fresh weight, **(D)** flower fresh weight, **(E)** total fresh weight, **(F)** stem dry weight, (G) leaf dry weight, **(H)** flower dry weight, **(I)** total dry weight, **(J)** days to visible bud, **(K)** days to first bud color, **(L)** days to sepal reflex, **(M)** days to flower. *Fig. 1 continued next page.*

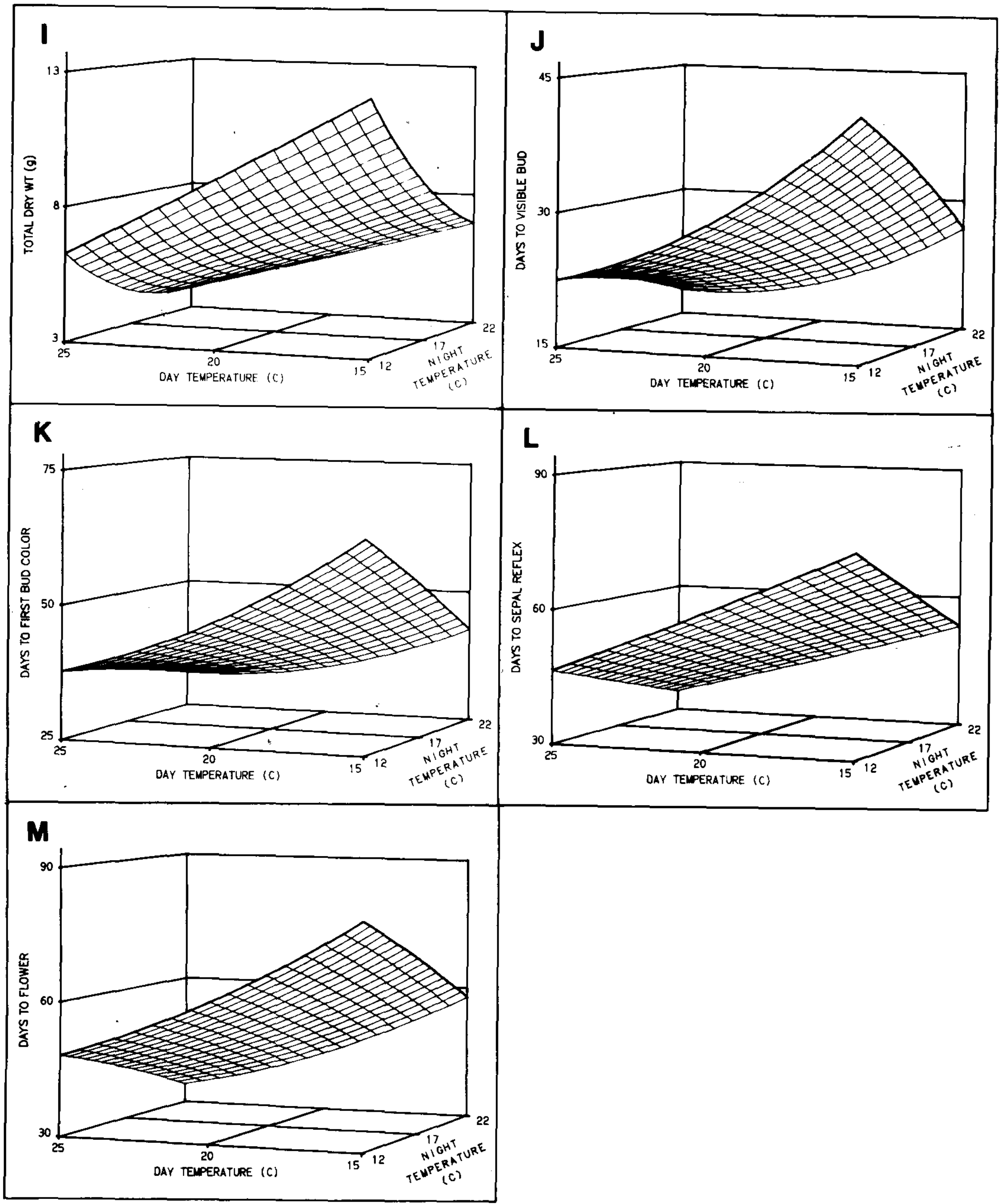

Fig. 1. *Cont.*

bud. Flower development was measured for each plant by recording days from pinch until visible bud, first bud color, sepals were reflexed at 90° from main stem axis, and until flowering.

Statistical approach

Treatment combinations of PPF, DT, and NT were selected according to the central composite rotatable experimental design (Myers, 1976) (Table 1). The center point (treatment 6) was repeated five times to estimate experimental error. Treatments were randomly selected to be conducted in one of two growth chambers; treatments were not blocked.

Second-order polynomial equations were fit to the data by SAS data analysis (SAS, Cary, N. C.) using linear, quadratic, and cross-product terms of X_{PPF}, X_{DT}, and X_{NT} (coded values of PPF, DT, and NT) to predict values of the plant characteristics at time of flowering. The higher-order interactions were considered nonsignificant and were not included in the model. These equations allowed response surfaces to be generated for each characteristic. Canonical analysis was performed on each equation by the SAS procedure RSREG. The stationary point (x_0), eigenvalues, (λ), and the orthogonal matrix of rotation (M) were determined as described by Myers (1976).

The response surface was then rewritten in the canonical form:

$Y = Y_0 + \sum_{i=1} \lambda_i w_i^2$ Where k = 3, y = estimated response at some set of x vector values, y_0 = estimated response at the stationary point x_0 vector, λ_i = eigenvalue (characteristic root) of the matrix containing the coefficients of the quadratic and cross-product terms of the quadratic fitted response surface equation, and w_i = component of the response in the direction of the new w_i-axis.

The M matrix transforms from the original x-coordinate sys-

Table 5. Coded and actual values for the stationary point for the canonical form, along with predicted values at the stationary point, and the associated eigenvalues and eigenvectors.

	Stationary point values[z]										
	Coded			Actual							
Characteristic	X_{PPF}	X_{DT}	X_{NT}	PPF	DT	NT	Stationary point	Eigenvalues	Eigenvectors (M matrix)		
Node no.	2.57	0.520	1.24	368	21.6	20.7	11.5	$\lambda_1 = 0.1048$	−0.3042	0.09025	0.9483
								$\lambda_2 = -0.08221$	0.6787	0.7191	0.1493
								$\lambda_3 = -0.1612$	0.6684	−0.6891	0.2800
Stem diam	−22.3	−3.12	−12.4	−1500	10.6	−20.2	−0.888	$\lambda_1 = 0.1782$	0.2595	0.7214	−0.6420
								$\lambda_2 = 0.01089$	0.9304	−0.008552	0.3664
								$\lambda_3 = -0.04901$	−0.2589	0.6924	0.6734
Stem length	0.693	−0.143	0.128	227	19.6	17.4	53.8	$\lambda_1 = 2.476$	−0.06594	−0.2277	0.9715
								$\lambda_2 = -0.3434$	0.3739	0.8970	0.2357
								$\lambda_3 = -2.058$	0.9251	−0.3788	−0.02599
Stem fresh wt	−4.87	12.4	0.727	−190	57.2	19.2	−5.40	$\lambda_1 = 0.4502$	−0.2671	−0.05605	0.9620
								$\lambda_2 = 0.1366$	0.9621	−0.07319	0.2628
								$\lambda_3 = 0.04305$	0.05568	0.9957	0.07347
Leaf fresh wt	−0.498	3.49	1.64	138	30.5	21.9	4.79	$\lambda_1 = 0.5460$	−0.5226	0.8341	0.1763
								$\lambda_2 = 0.3227$	0.06998	−0.1641	0.9840
								$\lambda_3 = -0.3218$	0.8497	0.5266	0.02741
Flower fresh wt	2.08	9.41	2.79	331	48.2	25.4	0.381	$\lambda_1 = 0.8304$	0.01605	−0.1992	0.9798
								$\lambda_2 = 0.1177$	0.03869	0.9793	0.1984
								$\lambda_3 = -0.7581$	0.9991	−0.03473	−0.02343
Total fresh wt	1.02	7.14	2.01	252	41.4	23.0	6.04	$\lambda_1 = 1.576$	−0.01797	−0.1220	0.9924
								$\lambda_2 = 0.5774$	−0.2793	0.9536	0.1121
								$\lambda_3 = -0.7864$	0.9600	0.2752	0.05120
Stem dry wt	−1.76	−9.50	3.18	43	−8.50	26.5	2.61	$\lambda_1 = 0.09879$	−0.3786	0.1061	0.9195
								$\lambda_2 = 0.01309$	0.8094	0.5198	0.2733
								$\lambda_3 = -0.02772$	−0.4489	0.8477	−0.2826
Leaf dry wt	0.990	1.71	4.07	249	25.1	29.2	1.85	$\lambda_1 = 0.1523$	−0.3737	0.6708	0.6406
								$\lambda_2 = -0.04486$	0.2326	−0.6008	0.7648
								$\lambda_3 = -0.1021$	0.8979	0.4348	0.06846
Flower dry wt	2.52	2.31	0.597	364	26.9	18.8	1.60	$\lambda_1 = 0.1583$	0.09453	0.2346	0.9675
								$\lambda_2 = 0.01918$	0.3290	0.9099	−0.2528
								$\lambda_3 = -0.1397$	0.9396	−0.3422	−0.008806
Total dry wt	2.24	−8.20	6.84	343	−4.60	37.5	9.90	$\lambda_1 = 0.3350$	−0.1345	0.3920	0.9101
								$\lambda_2 = -0.02857$	0.1565	0.9153	−0.3711
								$\lambda_3 = -0.1792$	0.9785	−0.09254	0.1845
Days to visible bud	0.926	2.59	−1.37	244	27.8	12.9	21.1	$\lambda_1 = 1.156$	0.08559	0.9513	0.2962
								$\lambda_2 = 0.2729$	0.9740	−0.01734	−0.2258
								$\lambda_3 = -0.4527$	0.2096	−0.3079	0.9281
Days to first color	0.912	2.96	−1.08	243	28.9	13.8	33.9	$\lambda_1 = 1.443$	0.2191	0.9058	0.3627
								$\lambda_2 = 0.7438$	0.9600	−0.1337	−0.2459
								$\lambda_3 = -0.4887$	0.1742	−0.4021	0.8989
Days to sepal reflex	−0.355	5.20	6.96	148	35.6	37.9	16.8	$\lambda_1 = 0.5391$	0.1678	0.7395	0.6519
								$\lambda_2 = -0.3185$	0.4015	0.5527	−0.7303
								$\lambda_3 = -0.6250$	0.9003	−0.3843	0.2042
Days to flower	−1.91	5.97	−3.83	31.8	37.9	5.51	41.7	$\lambda_1 = 1.181$	0.2094	0.9400	0.2693
								$\lambda_2 = -0.2607$	0.5165	−0.3401	0.7858
								$\lambda_3 = -0.4364$	0.8303	−0.02544	−0.5567

[z] Conversion between coded and actual values by the formulas: $PPF = 175 + 75 \times X_{PPF}$; $DT = 20 + 3 \times X_{DT}$; $NT = 17 + 3 \times X_{NT}$.

tem to a new w-coordinate system (see Table *5)*. The columns of the M matrix are eigenvectors corresponding to the eigenvalues determined by the analysis. Canonical analysis determined the nature of the stationary point (the x_0 vector combination of x values that defines where the slope of the response surface is zero for all dimensions) and of the response surface simply by observing sign and magnitude of the A values (Myers, 1976).

Results and Discussion

The full quadratic regression models based on the means of 10 subsamples from each treatment were significant for all plant characteristics measured, except node number and stem length (Tables 2-4). The high percentage of variability explained by each regression model was indicated by high R^2 values, all of which were above 0.75 for the significant models. Models fit for time of flower development were highly significant and had R^2 values exceeding 0.99 (Table 4). The response surface for stem diameter revealed small-diameter stems occurred under both high DT and NT (Fig. 1A), while large-diameter stems were promoted if low DT (15C) was used in combination with high NT (22C). Stem diameter was also enhanced by increased PPF, since a response surface corresponding to the highest PPF

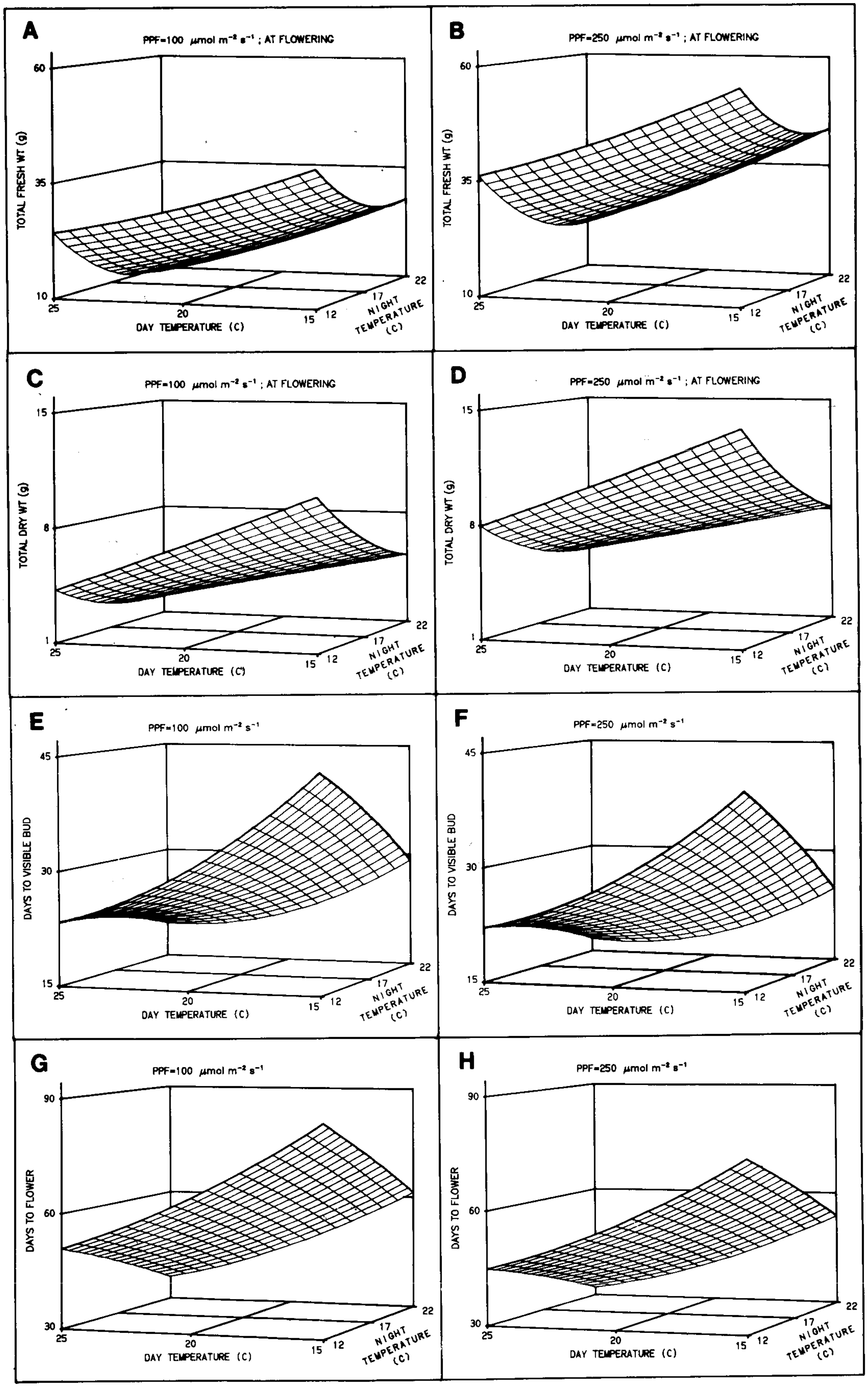

Fig. 2. Response surfaces for four plant characteristics of *Rosa hybrida* at flowering for two selected PPF levels under constant controlled environment conditions over the time of development. **(A)** Total fresh weight for PPF = 100 μmol·m^{-2}·s^{-1} **(B)** total fresh weight for PPF =250 μmol·m^{-2}·s^{-1} (C) total dry weight for PPF = 100 μmol·m^{-2}·s^{-1}, **(D)** total dry weight for PPF = 250 μmol·m^{-2}s^{-1}, **(E)** days to visible bud for PPF = 100 μmol·m^{-2}·s^{-1}, **(F)** days to visible bud for PPF = 250 μmol·m^{-2}·s^{-1}, (G) days to flower for PPF = 100 μmol·m^{-2}·s^{-1}, **(H)** days to flower for PPF = 250 μmol·m^{-2}·s^{-1}.

Fig. 3. Two representative rose plants from a repetition of the design center point (treatment 6:175 µmol·m^{-2}·s^{-1} PPF, 20C DT, and 17C NT), showing flower size and quality at time of flowering.

predicted greater stem diameter over the design space as compared to the midpoint level of PPF.

Response surfaces were similar in shape for both fresh and dry weights of the stem, leaves, flower bud, and total flowering stem (Fig. 1B–I). All response surfaces were saddle shapes by mathematical definition, except for stem fresh weight, which was a minimum or bowl shape. However, the shapes of the surfaces are not readily apparent since the stationary points are located a considerable distance outside the design space (Table 5). The least fresh and dry weights for all plant parts occurred at the highest DT (25C) and highest NT (22C), while greatest fresh and dry weights occurred for the lowest combinations of DT (15C) and NT (12C) (Fig. 1B-I). Environments that promoted increased quality, as measured by greater stem diameter as well as greater fresh and dry weights, also retarded flower development. This was illustrated for all flower development criteria, including time from pinch until visible bud, first bud color, sepal reflex, and flower harvest (Fig. 1J–M). Under the constant environmental conditions provided from pinch until anthesis, time until anthesis was very nearly double the time until visible bud for all environments (Fig. 1 J and M). This general rule would not be expected to apply precisely under greenhouse growing conditions, since seasonal weather changes would create different environments pre- and postvisible bud.

Armitage and Tsujita (1979a) concluded that increases in total fresh weight of flowers under supplemental PPF (158 µmol·m^{-2}·s^{-1}) resulted in increased stem diameter; yet, our study revealed increased fresh and dry weights of stems, leaves, and flower buds, as well as increased stem diameter, under higher PPF (250 µmol·m^{-2}·s^{-1}). Although stem length has been observed to be reduced under supplemental PPF (Armitage and Tsujita, 1979a; Carpenter and Anderson, 1972; White and Richter, 1973), no significant differences for stem length were observed in our study (data not shown). Yield, as measured by the number of roses produced over time, has been shown to increase under supplemental PPF (Armitage and Tsujita, 1979a, 1979b; Butt and Tsujita, 1986; Carpenter and Anderson, 1972; Cockshull, 1975; Holcomb and Arteca, 1987; Tsujita, 1982; White and Richter, 1973), while Mattson and Widmer (1971) and Post and Howland (1946) found natural variation in solar radiation to similarly influence rose yield. In contrast, cultural methods in this study did not allow more than one flower to develop per plant, thereby limiting the observed yield. If yield is defined in terms of total carbon fixed into dry matter, then increased yield was observed when PPF was increased for this study as well. Irradiated rose plants in the greenhouse partition additional photosynthates into several sinks, thereby creating more flowering stems, each having little or no increases in weight (Armitage and Tsujita, 1979a; Holcomb and Arteca, 1987; Tsujita, 1982; White and Richter, 1973). In these instances, however, calculation of the quality index (QI = yield × weight/length), as described by Tsujita (1982), accounts for the significant increases in carbon fixed by the plants receiving greater PPF.

Plants in our experiment increased in fresh and dry weights of stems, leaves, and flower buds under increased PPF (Fig. 2A–D), with no significant differences in partitioning between plant parts, unless shoots were blind, as under 50 µmol·m^{-2}·s^{-1} PPF. This result contrasts with the findings of Butt and Tsujita (1986), where a greater percentage of both fresh and dry matter was partitioned to the stem as PPF increased. Increased PPF also reduced the number of days until visible bud and flower over the design space (Fig. 2E–H). In particular, of the plants grown under 50 µmol·m^{-2}·s^{-1} in treatment 1 (Table 1), only one of the 10 plants grown to anthesis actually flowered; the remaining nine were blind, which indicates that PPF was indeed limiting in this lowest PPF treatment. Analyses conducted in this study used measurements from the single flowering plant as a representative mean for treatment 1. This did not influence the statistical significance of the regression and canonical analyses since the analyses used the means of the treatments for deriving the sums of squares upon which statistical tests were conducted. Overall, the model 10-cm pot system using single-stem plants produced flowers of size and quality similar to greenhouse production. Two representative plants from a repetition of the design center point illustrate the form and quality of typical flowers grown using these cultural techniques in growth chambers (Fig. 3).

Budbreak and anthesis of hybrid tea-rose seedlings has been reported to be delayed under low temperatures (DeVries et al., 1986). The delay of shoot growth and bud development to anthesis under low temperatures was confirmed with this study using ‘Royalty’. However, the increased accumulation of fresh and dry weights in low DT and NT indicated quality was improved relative to higher temperatures. Hanan (1979) found that very low temperatures (4.4 and 10C) used in a split NT regime actually decreased quality, as measured by average stem length grade, but subsequently raising NT to 16.7C increased the yield of flowers with longer stems. Since the lowest DT and NT in this study were 15 and 12C, respectively, the adverse effect of very low temperatures was not observed, while the increased dry matter accumulation by plants at 12 to 17C was evident as compared with the dry matter accumulation at temperatures of 20 to 25C.

Quadratic regression models developed from the data allowed for a simple representation of plant response to the environment. These models apply specifically for constant environmental conditions from the time of pinching until anthesis. The general trends involving interactions between PPF, DT, and NT were conveniently represented as response surfaces that were easily interpretable. A more complex group of quadratic equations representing growth over 10-day periods should prove useful in formulating a dynamic model to predict growth over time under variable environments, such as in a greenhouse.

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