J. Amer. Soc. Hort. Sci. 104(6):812–825. 1979.

Relative Efficiency of High- and Low-pressure Sodium and Incandescent Filament Lamps Used to Supplement Natural Winter Light in Greenhouses[1]

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Additional index words. lighting, controlled environments, radiation, photosynthesis, photomorphogenesis, energy utilization.

Abstract. **The relative efficiencies of high-pressure (HPS) and low-pressure sodium (LPS) lamps for plant growth were determined for 32 species of foliage and flowering plants in greenhouse under winter conditions at 37°N latitude. HPS with a relatively wide spectral emission peaking at 589 nm, and low-pressure sodium (LPS) with a monochromatic line at 589 nm were compared at 42 W/m^2 irradiance in the 400-700 nm region for various lengths of time at various times of day. Although radiation in the far-red region (700-800 nm) differed, HPS and LPS equally accelerated rates of increase in fresh weights, and heights, and flowering of most herbaceous and tropical foliage plants evaluated. High-pressure sodium and LPS were ineffective, however, in promoting growth of deciduous trees and some woody plants and had no more effect than exposure of the plants to natural winter days with 0.9 W/m^2 from incandescent lamps for 8 hrs (2000-0400) night interruption (long day controls). After 16 hours, about half the species showed photomorphogical differences between plants grown at intensities of 21 and plants grown at 42 W/m^2 from LPS. All showed significantly better growth characteristics (fresh weight, height, early flowering) than the long day controls. Lighting during the day or night (42 W/m^2 from 0800-1600 or from 2000-0400) was equally effective in promoting growth responses with 15 of the 32 species evaluated. Night lighting was more effective than day lighting with 10 of the 32 species tested. The majority of the species grew equally well when lighted 16 hours daily (0800-2400) with 21 W/m^2 or 8 hours daily (2000-0400) with 42 W/m^2. Effectiveness of the lighting was generally unrelated to the photoperiodic requirements of the plants. Many of the plants, which were previously classified as day-neutral (DN), flowered as if they were long day plants. Such day-neutral plants apparently required adequate light (intensity and duration) for photosynthesis. Increased daylength alone, without regard to intensity, was not sufficient to accelerate growth and early flowering of day-neutral plants. Since HPS and LPS were equally effective on most species tested, we concluded that light quality was less important than total irradiation (energy) for the growth and early flowering of many herbaceous plants.**

Supplemental lighting of plants in greenhouses dates from 1893. At that time a practical version of the carbon-arc lamp (INC) had been invented and L. H. Bailey (3) observed the acceleration of flowering of several horticultural plants by light at night. Garner and Allard in 1920 (16) differentiated the primary day-night regulatory action of light, sun or incandescent-filament lamps, from the ancillary effects of mineral nutrition, temperature, and relative humidity. Today photoperiodic responses (vegetative or reproductive) of plants are well documented and night lighting is commonly used and widely practiced by growers (4, 5, 9, 12, 13, 19, 20).

Lighting supplemental to sunlight for photosynthesis in greenhouses, however, has not gained wide acceptance by commercial growers. There are many reasons for this. With the many new types and models of artificial lamps and fixtures that have been introduced, researchers as well as growers are overwhelmed with the problems of acquiring the best working equipment, deciding the correct location for the lamps above the plants, and selecting the best times of day and duration for the illuminations (6, 10, 17, 18). The growth responses of various plants are difficult to evaluate and utilize in plans for installations (1, 2, 4, 7, 8, 14, 15, 21, 22). The increase in productivity and/or quality of the plants must be large enough to justify the cost of installation, operation, and replacement of the lamps.

This paper reports the responses of 32 species of plants to supplemental greenhouse lighting with high- (HPS) and low-pressure sodium (LPS) and incandescent-filament (INC) lamps.

Materials and Methods

We selected representatives of various species of plants whose growth and flowering were or were not controlled by photoperiod. The short-day (SD) plants for flowering were *Alternanthera, Chlorophytum, Chrysanthemum, Coleus, Euphorbia,* and *Glycine.* The long-day (LD) plants for vegetative growth were *Buxus, Chamaecyparis,* and *Ilex.* The LD plants for flowering were *Begonia, Hordeum, Lactuca, Petunia,* and *Sinningia.* The daylength intermediate plant for flowering was *Saintpaulia.* The previously nonresponsive (DN) plants were *Ageratum, Camellia, Carya, Dizygotheca, Gossypium, Hydrangea, Juniperus, Lycopersicon, Pelargonium, Pilea, Rosa, Solanum, Tagetes, Taxus, Thuja, Tsuga,* and *Zebrina.*

Plants were grown from cuttings in the greenhouse and maintained in vegetative growth until they were used experimentally. The SD plants *(Alternanthera, Chlorophytum, Chrysanthemum,* and *Euphorbia)* were grown under natural light supplemented with 4 hr of light (night interruption) from incandescent lamps of 0.216 klx from 2000 to 0400 daily to

[1]Received for publication March 17, 1979. Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that may also be suitable.
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[3]Irradiances are reported in watts per square meter (W/m^2) in the wavelength regions from 400 to 700 nm and 700 to 850 nm (Table 1). μ E.S.M. for HPS and LPS may be obtained by multiplying Watts/m^{2}x5.

provide long days (LD). The LD and ND plants *(Begonia, Buxus, Chamaecyparis, Dizygotheca, Hydrangea, Ilex, Juniperus, Pilea, Rosa, Saintpaulia, Thuja,* and *Zebrina)* were covered with black sateen cloth nightly from 1600 to 0800 to give the plants SD.

Seeds of *Ageratum, Coleus, Glycine, Gossypium, Hordeum, Lactuca, Lycopersicon, Pelargonium, Petunia, Solanum,* and *Tagetes* were sown in 0.15m plastic pots containing a medium of equal parts of peat and vermiculite and amended with standard amounts of fertilizer and ground dolomitic limestone. After seeding, the pots were placed in a greenhouse under 24/18°C (day/night temperature) and ambient CO_2 at about 350 ppm. Growing media temperatures were maintained at 25°C day and night by means of a thermostatically controlled propagation mat. The pots were misted with tap water from 0800 to 1700 at a rate of 6 sec every 6 min. When the first true leaves had begun to expand, the seedlings of *Ageratum, Coleus, Lactuca, Lycopersicon, Pelargonium, Petunia, Solanum,* and *Tagetes* were transplanted individually to 0.10m plastic pots and placed on 8-hr days from 0800 to 1600. Seedlings of *Glycine, Gossypium,* and *Hordeum* had been planted directly in 0.15m plastic pots and were thinned to one seedling per pot. The seedlings were selected for uniformity and experiments were started as soon as the plants resumed growth. Plants of the above species were grown in a greenhouse maintained at a day/night temperature of 20°C. Some were exposed to natural light (8.9 to 12 hours), which served as a natural winter day treatment (Treatment 2 in Tables 1 and 2).

Irradiation treatments with HPS, LPS, and INC at various levels and durations were used (Table 1). Most of the light treatments in the greenhouse were selected to provide 42 W/m² (400-700 nm)[3]. This was about half the energy we found to be most effective in our growth chamber studies for growth of plants (10). Light treatments consisted of 42 W/m² provided over 16 hr (0800-2400), or over 8 hr (0800-1600 or 2000-0400). To provide an equivalent energy treatment to the 8 hr exposures, another lot of plants was lighted with 21 W/m² provided over 16 hr (0800-2400). Some plants in the greenhouse were grown with 8 hr of natural irradiation and were covered with black cloth between 1600 and 0800. Other plants were grown on LD by interrupting the long dark period from 2000 ro 0400 with 0.216 klx of light from INC lamps. At the termination of the experiments, data were collected on the length of the primary mainshoots, the number of nodes on the meristems, fresh weight, and days to flower.

Results

The differences in sensitivity to light sources of the 32 species became apparent early in the experiment. The traditional LD treatment was 8.9 to 12 hr natural light plus 0.216 klx of INC from 2000 to 0400. Data from these plants were designated as the 100% response or baseline. This photo-environment produces LD effects on most plants when growing time is sufficient but the experiments reported here generally did not last long enough to provide such photoperiodic effects (early flowering, delayed flowering, vegetative growth or dormancy). The growth responses (height, weight or flowering) to supplementary lighting with high- and low-pressure sodium lamps were apparent from the beginning of the tests and occurred at rates that previously have been associated only with controlled-environment studies (10, 17, 18). The lighting supplemental to the natural days of winter provided an environment in which height or weight increases were much faster than rates previously observed for these species under conventional greenhouse conditions. The responses to HPS and LPS will be compared in the following ways: HPS and LPS equal energies; LPS with energy halved; LPS with equal energies during day or night; and LPS with equal energies 8 or 16 hr daily.

HPS and LPS with equal energies. The majority of the 32 plant species exhibited equal growth responses to supplemental lighting (HPS, LPS) of 42 W/m² (400-700 nm) from 0800 to 2400 (Table 2, treatments 4 & 5). Fresh weight increased in *Ageratum, Begonia, Chlorophytum, Chrysanthemum, Coleus, Euphorbia, Glycine* (Fig. 1A), *Gossypium, Hordeum* (Fig. 1A), *Lactuca* (Fig. 1B), *Lycopersicon* (Fig. 1B), *Pelargonium, Rosa* (Fig. 2B), *Solanum, Tagetes* (Fig. 1C), and *Zebrina;* heights increased in *Buxus, Dizygotheca, Ilex, Juniperus* (Fig. 2A), and *Thuja.* Plants of *Chamaecyparis* were more compact and highly branched in response to HPS and LPS supplemental lighting than plants without supplemental sodium lighting. HPS was more effective than LPS on vegetative growth of *Alternanthera* while LPS was more effective than HPS on the vegetative growth of *Hydrangea* (Fig. 2A) and promotion of early flowering of *Petunia* (Fig. 1C), *Saintpaulia,* and *Sinningia* (Fig. 2B). We observed no measurable growth or flowering responses with plants of *Camellia, Carya, Pilea, Taxus,* and *Tsuga* to any of the treatments.

LPS with energy halved. The majority of the 32 plant species exhibited a significantly greater growth response to 42 (400-700 nm) than to 21 W/m² LPS from 0800 to 2400 (Table 2, treatments 5 & 8). This response was observed with the fresh weight increases of *Ageratum, Coleus, Euphorbia, Glycine, Hordeum, Lactuca, Lycopersicon, Petunia, Rosa, Solanum,* and *Tagetes;* the earlier flowering of *Saintpaulia* and *Sinningia;* and the height increases of *Buxus, Ilex,* and *Thuja.* Some of the plant species grew equally well as measured by fresh weight under the two light levels. We observed this equality in the increases in the fresh weight of *Alternanthera, Begonia, Chlorophytum, Chrysanthemum, Gossypium, Pelargonium,* and *Zebrina;* in the increased heights of *Dizygotheca, Hydrangea,* and *Juniperus;* and in the dense, compact growth of *Chamaecyparis.*

Table 1. Supplementary lighting treatments used.

Treatment	Daylength + type of radiation[z]	Duration		Illuminance* (klux)	Irradiance (W/m²)	
		Hr.	Time		400-700 nm	700-850 n
1.	SD	8	0800-1600	–	–	–
2.	ND	–	–	–	–	–
3.	ND + INC	8	2000-0400	0.216	0.9	1.0
4.	ND + HPS	16	0800-2400	17	42	15.5
5.	ND + LPS	16	0800-2400	22	42	6.0
6.	ND + LPS	8	0800-1600	22	42	6.0
7.	ND + LPS	8	2000-0400	22	42	6.0
8.	ND + LPS	16	0800-2400	11	21	3.0

[z]Measured 0.25 m above bench SD = Short Day (8 hr); ND = Natural Day; INC = Incandescent; HPS = High-Pressure Sodium; LPS = Low-Pressure Sodium.

Table 2. Effects of supplementary lighting treatments on growth responses of 32 species.

Species Variable	Treatment[z] 1	2	3	4	5	6	7	8
Ageratum houstonianum Mill. **DN**[y]								
Ageratum 'Blue Blazer'								
Weight (g)	8.6	7.6	8.7	16.7	24.7	11.7	15.3	16.0
(%)	99ab[x]	84a	100a	192d	283d	134b	176c	161c
Height (cm)	9.3	9.0	9.0	10.7	14.7	10.0	9.3	10.0
(%)	103a	100a	100a	119a	163b	111a	103a	111a
Nodes (no.)	16.0	16.7	15.3	18.0	17.3	18.0	17.3	16.3
(%)	105	109	100	118	113	107	118	113 N.S.
Alternanthera ficoidea (L.) R. Br. ex. Roem. & Schult. **SD-F**								
Yellow Calico 'Aurea Nana'								
Weight (g)	9.6	9.8	9.5	28.0	18.0	13.0	17.0	17.5
(%)	101a	103a	100a	295c	189b	137ab	179b	184b
Height (cm)	7.5	8.0	7.5	11.5	9.3	8.3	9.8	9.0
(%)	100a	107a	100a	153c	124b	111a	131b	120ab
Nodes (no.)	20.5	20.3	19.0	23.8	22.2	21.5	24.0	21.5
(%)	108a	107a	100a	125b	117ab	113ab	126b	113ab
Begonia foliosa HBK. – **LD-F**								
Fernleaf Begonia								
Weight (g)	11.9	11.8	11.8	34.5	37.5	20.8	38.5	32.5
(%)	101a	100a	100a	292c	318c	176b	326c	275c
Height (cm)	18.7	18.3	18.5	24.0	23.0	23.0	28.0	26.7
(%)	101a	99a	100a	130b	124ab	124ab	151c	144c
Nodes (no.)	17.2	17.5	16.3	19.2	19.2	18.3	20.0	18.5
(%)	106	107	100	118	118	112	123	113 N.S.
Buxus microphylla Siebold. & Zucc. – **LD-V**								
Japanese Boxwood 'Green Beauty'								
Height (cm)	18.1	18.4	18.4	25.6	23.6	18.2	18.6	18.8
(%)	98a	100a	100a	139b	128b	99a	101a	102a
Width (plant)	9.4	9.8	9.8	15.6	17.6	14.8	15.6	16.0
(%)	96a	100a	100a	159b	180b	151b	159b	163b
Chamaecyparis pisifera (Siebold. & Zucc.) Endl. – **LD-V**								
False Cypress 'Cyanoviridio' Dwarf Blue								
Height (cm)	14.0	32.0	33.1	26.4	25.3	34.1	29.3	27.2
(%)	42a	97c	100c	80b	76b	103c	89b	82b
Width (plant)	8.0	17.5	18.3	32.1	33.1	17.3	27.1	26.4
(%)	44a	97b	100b	175c	181c	95b	148bc	144bc
Chlorophytum comosum (Thunb.) Jacques – **SD-F** and Runners								
Spider Plant 'Variegatum'								
Weight (g)	14.5	13.8	16.3	21.5	23.8	27.5	23.8	28.7
(%)	89a	85a	100a	132b	146b	169b	146b	176b
Height (cm)	5.7	6.3	5.5	6.5	6.3	6.8	7.8	6.8
(%)	90a	87a	100a	103a	100a	108a	123b	108a
Node (no.)	11.2	11.5	11.0	13.3	14.5	14.3	14.5	14.3
(%)	102a	105a	100a	121ab	132b	130b	132b	130b
Chrysanthemum x *morifolium* Ramat. – **SD-F**								
'Goldburst Mefo'								
Chrsanthemum-break (no.)	8.6	9.5	8.0	9.9	8.8	8.8	8.9	9.1
(%)	111a	119a	100a	124b	110a	110a	111a	114a
Break wt (g)	3.3	3.1	3.9	5.5	6.6	4.9	6.0	6.3
(%)	85a	79a	100b	141c	169c	126c	153c	162c
'Streamer'								
Break (no.)	8.0	7.4	6.8	7.8	7.0	7.0	8.0	7.8
(%)	118ab	108a	100a	115a	131b	103a	118ab	115a
Break wt (g)	4.8	5.0	4.6	8.5	8.6	6.1	7.5	6.9
(%)	104a	109a	100a	185c	187c	132ab	163c	150b

(continued)

Table 2. (continued)

Species Variable	1	2	3	4	5	6	7	8
	Treatment[z]							
'Iceberg'								
Shoot wt (g)	3.0	2.0	3.0	3.9	5.0	3.5	3.6	4.1
(%)	100b	67a	100b	130bc	167c	117b	120b	137c
Shoot (no.)	6.1	5.5	5.2	7.2	7.8	6.5	7.6	7.1
(%)	117a	106a	100a	138b	150c	125b	146c	137b
Coleus x *hybridus* Voss. – SD-F								
Coleus 'Carefree Scarlet'								
Weight (g)	1.0	2.5	2.5	7.5	8.0	4.0	4.2	5.8
(%)	40a	100b	100b	300e	320e	160c	168c	232d
Height (cm)	5.0	17.3	20.5	58.7	40.3	21.1	21.8	52.3
(%)	24a	84a	100ab	286c	197c	103ab	106ab	255c
Dizygotheca elegantissima (Veitch) Vig. & Guill. – DN								
False aralia								
Height (cm)	7.3	7.3	8.1	12.9	12.6	10.1	10.5	11.4
(%)	90a	90a	100a	159b	156b	125b	130b	141b
Euphorbia pulcherrima Willd. ex. Kl. – SD-F								
Poinsettia 'Annette Hegg Supreme'								
Weight (g)	3.3	4.7	4.7	9.3	9.3	7.3	7.0	7.0
(%)	70a	100b	100b	198d	198d	155c	148c	148c
Shoot (no.)	4.7	5.3	5.0	5.3	4.7	5.0	6.0	6.3
(%)	94a	106a	100a	106a	94a	100a	120b	126b
Glycine max (L.) Merr. – SD-F								
Soybean 'Amsoy'								
Weight (g)	8.5	25.1	27.1	102.7	99.0	62.7	65.7	75.2
(%)	31a	93b	100b	379d	365d	231c	242c	277c
Height (cm)	20.3	41.3	41.7	80.5	80.0	67.2	46.5	69.3
(%)	49a	99b	100b	193c	192c	161c	183c	166c
Node (no.)	4.5	10.0	11.0	14.0	14.0	12.5	12.8	12.8
(%)	41a	91b	100b	127c	127c	114b	116b	116b
Gossypium hirsutum L. – DN								
Cotton 'Acala'								
Weight (g)	8.1	8.0	8.5	11.3	11.7	9.5	12.3	10.8
(%)	95a	94a	100a	133b	138b	112a	145b	127b
Height (cm)	22.0	27.3	27.1	22.5	25.0	25.7	31.5	25.3
(%)	81a	101b	100b	83a	92a	95ab	116c	93ab
Node (no.)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0 N.S.
(%)	100	100	100	100	100	100	100	100
Hordeum vulgare L. – LD-F								
Barley 'Atlas' (CI 4118)								
Weight (g)	16.4	22.5	27.1	115.2	110.3	62.1	81.3	72.1
(%)	61a	82a	100b	425e	407e	229c	300d	266c
Height (cm)	17.5	25.8	98.3	96.4	75.8	56.7	61.3	66.1
(%)	18a	26a	100c	98c	77b	58b	62b	67b
Hydrangea macrophylla (Thunb.) Ser. – DN								
Hydrangea								
Height (cm)	7.0	12.4	14.4	19.8	24.1	25.4	23.6	22.9
(%)	49a	86b	100b	138c	167d	174d	164d	159d
Ilex crenata Thunb. – LD-V								
Japanese Holly 'Greenthumb'								
Height (cm)	22.0	24.3	27.5	43.8	48.4	32.0	37.5	33.4
(%)	80a	88a	100b	159d	175d	116bc	136c	121bc
Plant width (cm)	20.0	24.3	24.0	46.0	45.6	34.0	37.8	34.3
(%)	83a	101b	100b	192d	190d	142c	160c	143c

(continued)

Table 2. (continued)

Species Variable	Treatment[z] 1	2	3	4	5	6	7	8
Juniperus virginia L. – **DN**								
Red Cedar 'Skyrocket'								
Height (cm)	21.2	26.6	26.9	38.4	32.6	26.4	31.8	32.6
(%)	79a	99b	100b	143c	121c	98b	118c	121c
Weight (g)	25.0	37.0	41.3	65.8	52.2	35.8	53.8	53.2
(%)	61a	90b	100b	160c	126c	87b	130c	129c
Plant width (cm)	2.8	4.8	5.6	9.8	11.2	5.4	10.2	6.6
(%)	50a	86b	100b	175c	200c	96b	182c	118bc
Lactuca sativa L. – **LD-F**								
Lettuce 'Grand Rapids'								
Weight (cm)	10.7	37.7	43.2	103.0	99.0	65.3	82.0	69.0
(%)	25a	87b	100b	238c	229d	151c	190c	160c
Height (g)	2.7	4.0	4.9	5.3	6.0	5.3	6.7	5.3
(%)	55a	82b	100b	108b	122c	108b	137c	108b
Leaf width (cm)	12.3	13.0	17.0	24.0	27.0	18.7	18.3	20.1
(%)	72a	76a	100b	141c	158c	110b	108b	118b
Lycopersicon lycopersicon Mill. – **DN**								
Tomato 'Patio'								
Weight (g)	11.8	20.0	21.2	41.0	36.5	33.7	32.7	38.3
(%)	56a	94b	100b	193d	172d	159c	154c	181d
Pelargonium x *hortorum* L.H. Bailey – **DN** (seed started February 25)								
Geranium 'Sprinter Scarlet'								
Flower date	May 18	May 25	May 31	April 30	April 30	May 19	May 2	May 11
Days to flower	82	89	95	64	64	83	66	75
Geranium 'Carefree Scarlet'								
Weight (g)	3.0	5.2	5.1	14.3	15.0	13.3	13.3	12.7
(%)	59a	102b	100b	280c	294c	260c	260c	249c
Height (cm)	2.3	3.0	3.0	4.3	5.0	5.0	5.2	4.8
(%)	77a	100b	100b	143c	167c	167c	173c	150c
Petunia x *hybrida* Vilm. – **LD-F**								
Petunia 'Pink Cascade'								
Weight (g)	24.0	40.6	44.7	62.3	77.8	65.7	70.0	68.5
(%)	54a	90b	100b	139c	174d	147c	136c	153c
Height (cm)	4.3	15.0	20.6	8.5	7.3	15.8	18.0	7.3
(%)	21a	73b	100c	41a	35a	77b	87b	35a
Node (no.)	21.8	24.5	24.3	23.3	25.0	24.5	24.5	25.3
(%)	90	101	100	96	103	101	101	104 N.S.
Pilea cadierei Gagnep. & Guillaum – **DN**								
Aluminum Plant								
Weight (g)	14.1	13.7	14.6	17.0	15.8	15.8	16.5	17.3
(%)	96	94	100	116	108	108	113	118 N.S.
Height (cm)	13.0	16.2	16.5	16.8	17.0	16.3	16.5	18.0
(%)	79a	98b	100b	102b	103b	98b	100b	109b
Node (no.)	104	100	100	107	107	107	107	107 N.S.
Rosa chinensis Jacq. – **DN**								
Rose 'Minima' Red Imp.								
Weight (g)	2.3	6.6	6.2	8.0	9.4	5.6	6.4	6.6
(%)	37a	106b	100b	129c	152c	90b	103b	106b
Flower date	Dec. 9	Dec. 6	Dec. 4	Dec. 6	Dec. 1	Dec. 16	Dec. 12	Dec. 12
Height (cm)	13.8	16.4	16.4	18.4	20.6	19.4	20.1	20.2
(%)	84a	100a	100a	112b	126c	123c	123c	118b
Saintpaulia ionantha Wendl. – **Daylength Intermediate**								
Ballet Violet 'Ulli'								
Days to flower	87d	87d	90d	58b	47a	66c	70c	56b

(continued)

Table 2. (continued)

Species Variable	Treatment[z] 1	2	3	4	5	6	7	8
Sinningia speciosa (Lodd.) Hiern. – LD-F								
Gloxinia 'Improved Red Velvet'								
Days to flower	139d	148d	148d	84b	73a	101c	106c	101c
Solanum melongena L. – DN								
Eggplant 'Black Beauty'								
Weight (g)	9.3	14.3	22.5	47.7	51.0	31.3	31.0	38.7
(%)	41a	64a	100b	212d	227d	139c	138c	172cd
Height (cm)	4.7	6.3	8.2	10.2	13.3	8.7	9.7	10.0
(%)	57a	77a	100b	130c	162d	106b	118c	122c
Node (no.)	7.3	7.0	7.2	10.0	9.7	8.0	9.0	8.3
(%)	101a	97a	100a	139b	135b	111ab	125b	115ab
Tagetes patula L. – DN								
French Marigold 'Sparky'								
Weight (g)	7.0	17.7	18.2	43.3	38.7	28.3	34.3	29.0
(%)	38a	97b	100b	238e	213e	155c	188d	159c
Height (cm)	9.3	11.3	14.7	12.7	12.0	9.7	12.3	10.7
(%)	63a	77a	100c	86b	82b	66a	84b	73a
Node (no.)	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
	100	100	100	100	100	100	100	100 N.S.
Thuja occidentalis L. – DN								
American Arborvitae 'Pyramidalis'								
Height (cm)	18.0	24.5	25.1	39.8	37.2	25.2	33.1	33.5
(%)	72a	98b	100b	159d	148d	100b	132c	133c
Width (g)	11.3	14.5	13.7	37.2	38.3	21.1	33.5	32.4
(%)	82a	105b	100b	272d	280d	154c	244d	236d
Zebrina pendula Schnizl. – DN								
Wandering Jew 'Purpusii'								
Weight (g)	14.7	18.8	17.9	28.5	31.0	22.3	21.2	25.3
(%)	82a	105b	100b	159c	173c	125c	118c	141c

[z]For explanation of treatments, see Table 1.

[y]LD-V = Long day, vegetative growth; LD-F = long day, flowering; SD-V = short day, dormant; SD-F = short day, flowering; DN = day length neutral.

[x]Mean separation, within rows, by Duncan's multiple range test, 5% level.

[w]Number shows is percent of Treatment 3.

LPS with equal energies during day or night. Growth of the majority of the 32 plant species was the same with supplemental LPS during the day (0800-1600) or during the night (2000-0400) at an intensity of 42 W/m^2 (400-700 nm) (Table 2, treatments 6 & 7). This was true of fresh weights of *Chlorophytum, Coleus, Euphorbia, Glycine, Lactuca, Lycopersicon, Pelargonium, Petunia, Rosa, Solanum,* and *Zebrina;* the early flowering of *Saintpaulia* and *Sinningia;* and the increased height of *Dizygotheca* and *Hydrangea.* Day supplemental lighting was not more effective than night lighting with any of the 32 species tested. Night lighting was more effective than day lighting in increasing the fresh weights of *Ageratum, Alternanthera, Begonia, Gossypium, Hordeum,* and *Tagetes.* Plants of *Ilex, Juniperus,* and *Thuja* were taller, while those of *Chamaecyparis* were more compact when lighted with HPS and LPS at night than during the day. Plants of *Buxus, Chrysanthemum,* and *Pilea* were non-responsive.

LPS with equal energies for 16 hr (day and night) and 8 hr (day). The 32 plant species were equally divided between those that did not and those that did grow better (height or weight increases, early flowering) under 16 hr of LPS (21 W/m^2 400-700 nm) during the day and night (0800-2400) than under 8 hr of equal energy (42 W/m^2) during the day (0800-1600) (Table 2, treatments 6 & 8). Fresh weight increases were equal with plants of *Chlorophytum, Euphorbia, Glycine, Lactuca, Pelargonium, Petunia, Rosa, Tagetes,* and *Zebrina;* height increases were equal with plants of *Dizygotheca, Hydrangea,* and *Ilex;* and flowering times were equally early with *Sinningia.* The 16-hr supplemental light exposure (21 W/m^2 for 16 hr, 0800-2400) was more effective than the 8-hr treatment (42 W/m^2 for 8-hr) in promoting increases in the fresh weight of *Ageratum, Alternanthera, Begonia, Coleus, Gossypium, Hordeum, Lycopersicon,* and *Solanum;* increased height of *Juniperus* and *Thuja;* compact growth of *Chamaecyparis;* and early flowering of *Saintpaulia.* None of the species tested (Table 2) grew better under the 8-hr day treatment than under the 16-hr day-night supplemental treatment. Neither supplemental light treatment affected the growth of *Buxus, Chrysanthemum* or *Pilea.*

LPS with equal energies for 16 hr (day and night) and 8 hr (night). Nineteen of the 32 species exhibited equal growth responses (height or weight increase, early flowering) to 16 hr of 21 W/m^2 LPS (0800-2400) and 8 hr of 42 W/m^2 LPS (2000-0400) (Table 2, treatments 7 & 8). Only *Coleus, Lycopersicon,* and *Solanum* weighed more and *Saintpaulia* flowered earlier when grown under a supplemental light treatment for 16 hr

(0800-2400) than when grown under 8 hr (2000-0400). The 8 hr supplemental light treatment during the dark was more effective than the 16 hr light and dark exposure with plants of *Hordeum, Ilex,* and *Tagetes.* No differences were observed in the growth responses of *Buxus* and *Pilea.*

Growth Responses – The growth responses of three types of plants were evaluated: i.e. annual plants with varying sensitivities to photoperiod, evergreen foliage plants from the tropics, and woody plants that can be adapted for seasonal growth in temperate regions. Supplemental lighting HPS and LPS accelerated the growth and early flowering of most annual plants such as DN *Ageratum, Gossypium, Lycopersicon, Pelargonium, Solanum,* and *Tagetes;* daylength intermediate *Saintpaulia;* and LD *Hordeum, Lactuca, Petunia,* and *Sinningia* (Table 2). The SD Plants *(Chrysanthemum, Coleus, Euphorbia,* and *Glycine)* continued vegetative growth but flowering was not completely inhibited because all four of the species (data not given) showed the first signs of initiating flowers at the termination of the experiments. Growth accelerated while the node numbers did not change in the foliage plants *Alternanthera, Begonia, Chlorophytum, Dizygotheca,* and *Zebrina.* The responses of the woody plants varied greatly from species to species. *Buxus, Ilex, Juniperus, Rosa,* and *Thuja* continued to grow throughout the rest period. Plants of *Hydrangea* continued vegetative growth when grown with supplemental HPS and LPS and went dormant when lighted with supplemental INC or natural days. Plants of *Chamaecyparis* continued the dense, compact, highly branched growth characteristic of these plants grown during the summer. None of the supplemental lighting treatments prevented the cessation of growth and formation of dormant growing points on plants of *Camellia, Carya,* and *Taxus.* Plants of *Tsuga* grew slowly under all treatments.

Discussion

Supplemental lighting in our greenhouses during the winter provided the light (radiation) needed to accelerate the growth of a wide range of annual tropical foliage, and woody plants. In our studies we assumed that at the latitude of 37°N, natural radiation of 700-850 nm was sufficient to meet the photomorphogenic requirements of most plants. Further, we used the natural winter day (8.9–12 hr) and interrupted the dark period with 8 hr of INC of low intensity from 2000 to 0400. We assumed that this photo-environment (illuminance) was sufficient for the plants to make maximum use of whatever photosynthate the plants produced. The responses of these plants were used as a basis for comparison of the relative photosynthetic effectiveness of the two types of sodium lamps.

The emission curve of the high-pressure sodium lamp (HPS) peaked in the orange-yellow region (6) and sloped downward into the red and green regions (6). As we have reported (9), HPS produced photoperiodic responses with many annual and woody plants. The low-pressure sodium lamp (LPS) emitted a single line at 589 nm (6) and acted as a red source when used to affect the photoperiodic responses of plants. The LPS action on short day plants was demonstrated only when a brief, intense interruption was given during the middle of a long dark period. Thus, the 2 lamps were very different. Both were particularly ineffective in promoting stem elongation and early flowering of long day plants.

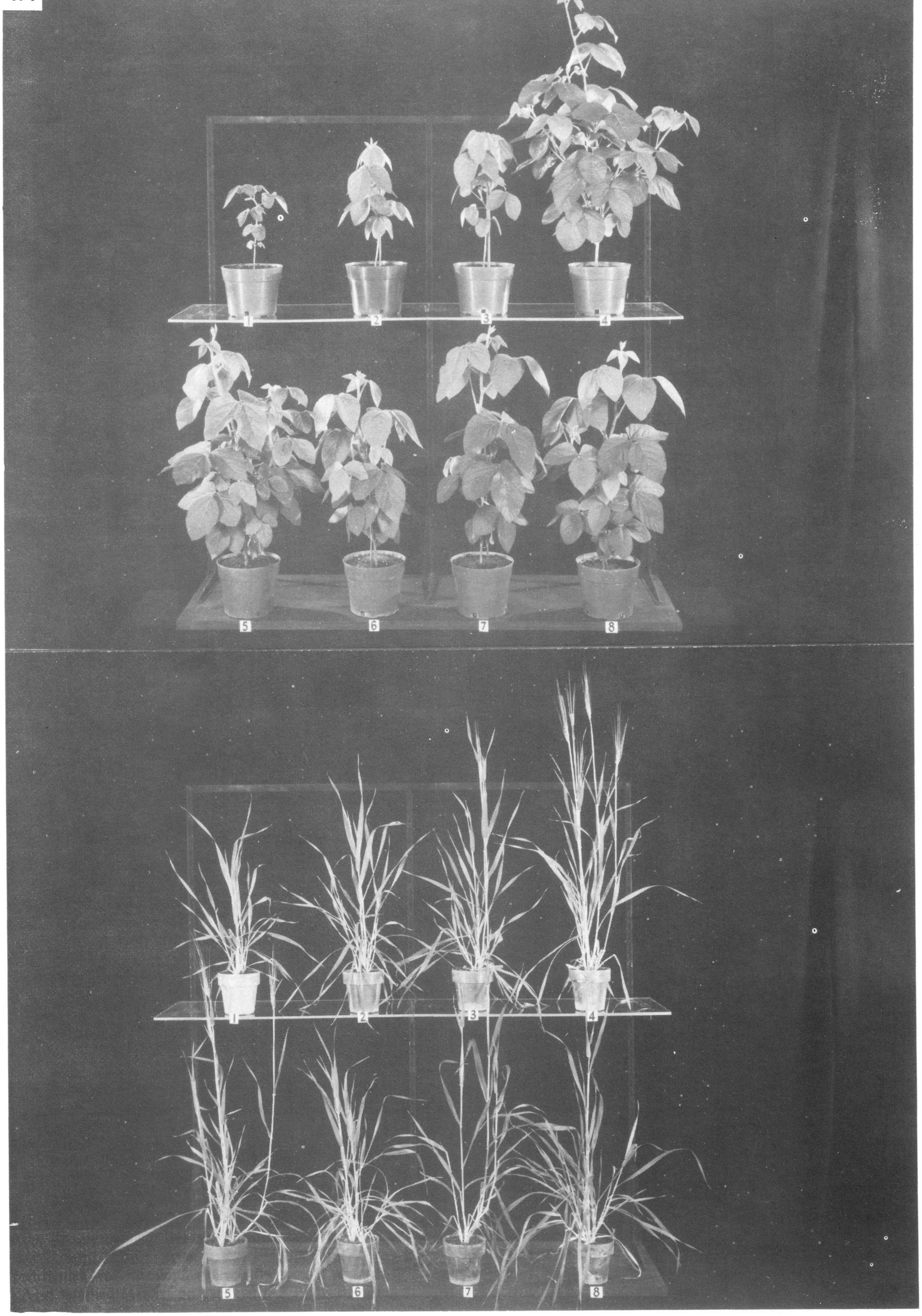
With this background, we concluded that HPS and LPS, when given as a supplemental light treatment in the greenhouse from morning (0800) to midnight (2400), were equally effective in initiating photosynthetic activity. Next we compared the lamps at 42 W/m^2 in the 400-700 nm region. HPS emitted about 3 times more energy in far-red (700-850 nm) than LPS (Table 1). HPS and LPS equally accelerated increased fresh weight, height and early flowering which were not correlated with radiation in the far-red region. The number of nodes initiated on the plants grown with the supplemental lighting, however, was not as large as the number of nodes reported by Krizek, et al. (17) in seedlings started in controlled environments. This showed that the HPS and LPS lighting were increasing the net photosynthesis (growth) of each leaf and stem on the plants rather than reducing the time required for leaf initiation. Thus, the natural light conditions, even though night interruptions with INC were given to create a LD photoperiodic effect, were inadequate for the plants to achieve their optimum rates of photosynthesis. The supplemental lighting treatments with HPS and LPS on some annual and tropical foliage plants increased the photosynthetic activity of the leaves and significantly increased fresh weights and heights, and accelerated flowering. Supplemental lighting with HPS and LPS of high-light requiring plants such as *Glycine* and *Hordeum* (Fig. 1A) also increased the rate of leaf formation and resulted in the largest percentage gains in fresh weight of any of the plants tested. Photosynthesis and rate of node formation both increased in *Glycine* and *Hordeum.* Only photosynthesis (as measured by node numbers and net increase in weight) increased in most of the other annual plants and tropical foliage plants.

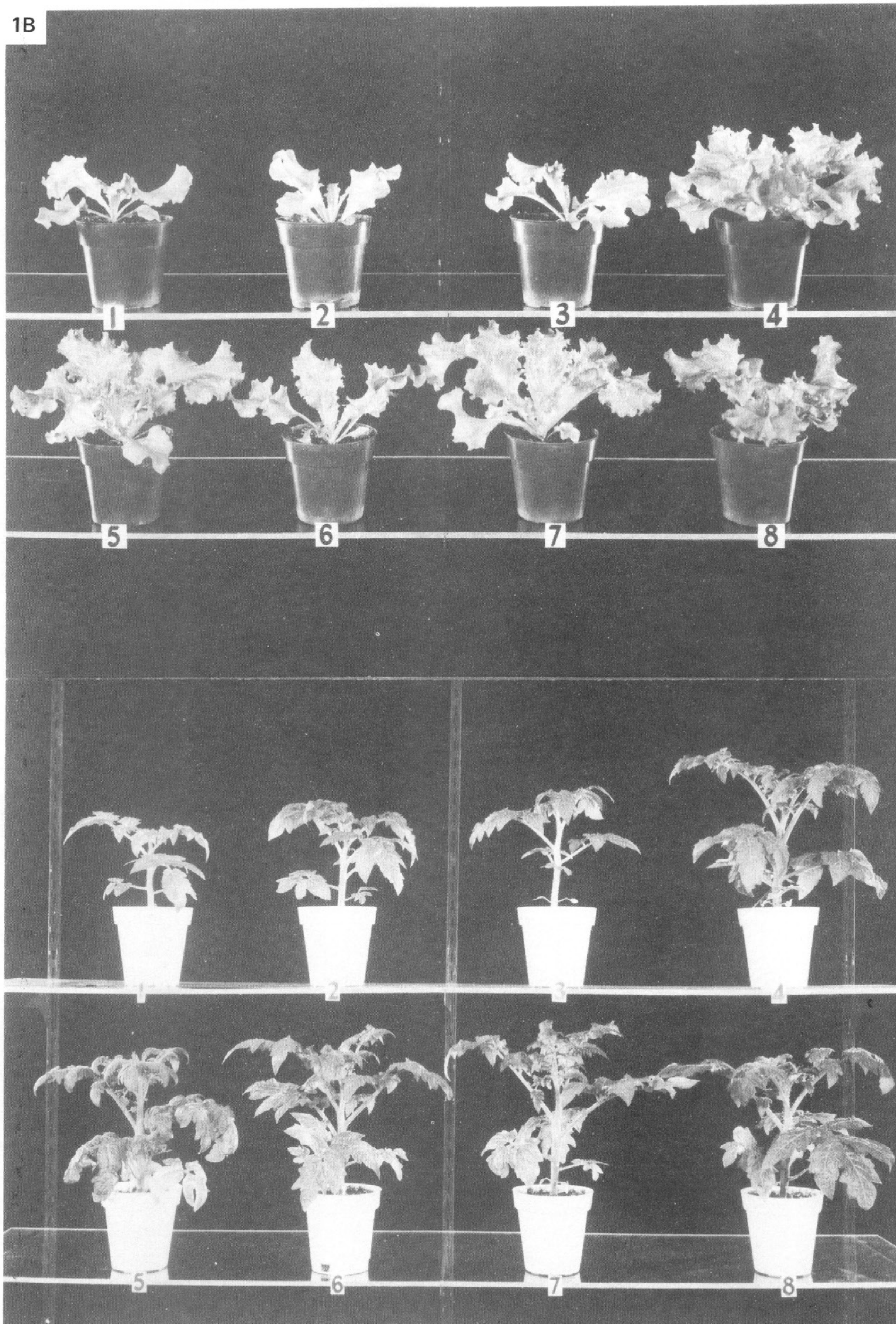
This dependency on supplemental lighting for achievement of rapid growth was further supported by the LPS treatments involving 21 W/m^2 for 16 hr and 42 W/m^2 for 8 hr during the day (0800-1600) and the night (2000-0400). About half of the plant species showed differences among treatments. All grew significantly better (fresh weight, height, early flowering) (Fig. 1B, C) than the long day INC controls. Lighting with HPS and LPS during the day or night was equally effective in promoting growth responses with 15 of the species. None of the plant species tested, however, exhibited a greater response to day than to night supplemental lighting. Night lighting was more effective than day lighting with 10 of the species tested. The majority of species grew equally well when lighted 16 hr daily (0800-2400) with 21 W/m^2 or 8 hrs daily (2000-0400) with 42 W/m^2.

Effectiveness (as measured by vegetative growth or flowering time) of the supplemental lighting in the greenhouse was generally unrelated to the observed photoperiodic responses of the plants. We observed that supplemental light with HPS and LPS (day or night) equally accelerated growth of SD plants *Coleus, Euphorbia,* and *Glycine* (Fig. 1A) and growth of LD plants *Lactuca* (Fig. 1B), *Petunia* (Fig. 1C), and *Sinningia* (Fig. 2B). Only the LD plant *Hordeum* (Fig. 1A) grew better when lighted with HPS and LPS at night (2000-0400) than when lighted during the day (0800-1600). The long term effects of the lighting at night, however, were to delay the flowering of the SD plants and to accelerate the flowering of LD plants. Many of the day neutral plants (annual and tropical foliage plants), as previously classified, grew and flowered as if they were LD plants. This is apparently how most day neutral and daylength sensitive plants grow under natural conditions in greenhouses or out-of-doors. They require adequate light (sufficient energy and duration) for photosynthesis. The HPS and LPS lamps as supplemental sources in greenhouses were

Fig. 1. (A) Plants of *Glycine* (upper) and *Hordeum* (lower); (B) *Lactuca* (upper) and *Lycopersicon* (lower); and (C) *Petunia* (upper) and *Tagetes* (lower) were given various light treatments. Treatments were 1. Short days (SD) (8 hr); 2. Natural days (ND) (8.9-12 hr); 3. ND + 8 hr 216 lx Incandescent lamp (2000-0400); 4. ND + 16 hr 17,000 lx High-Pressure Sodium lamp (HPS) (0800-2400); 5. ND + 16 hr 22,000 lx Low-Pressure Sodium lamps (LPS) (0800-2400); 6. ND + 8 hr 22,000 lx LPS (0800-1600); 7. ND + 8 hr 22,000 lx LPS (2000-0400); and 8. ND + 16 hr 11,000 lx LPS (0800-2400).

1A




1B
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1C

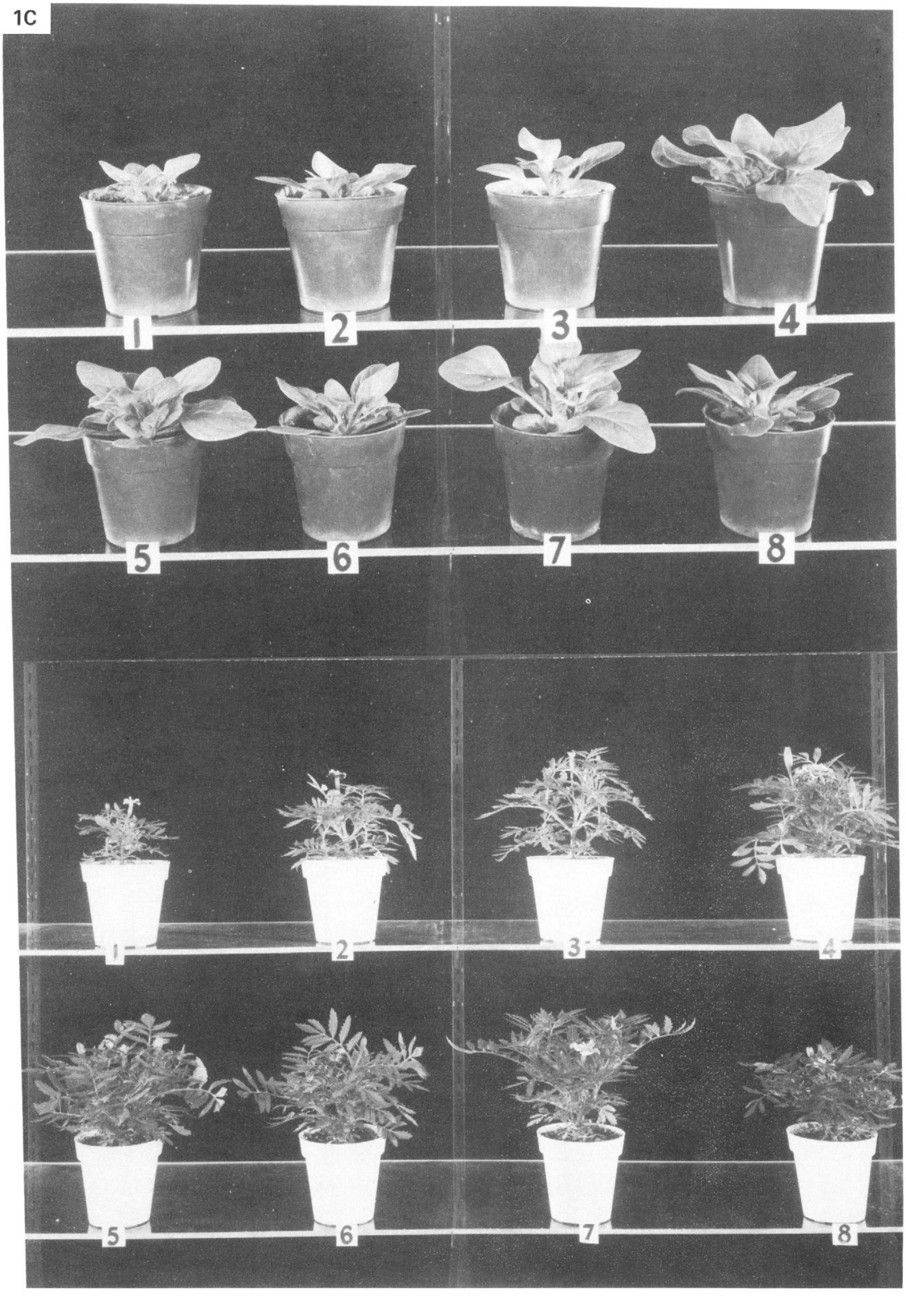
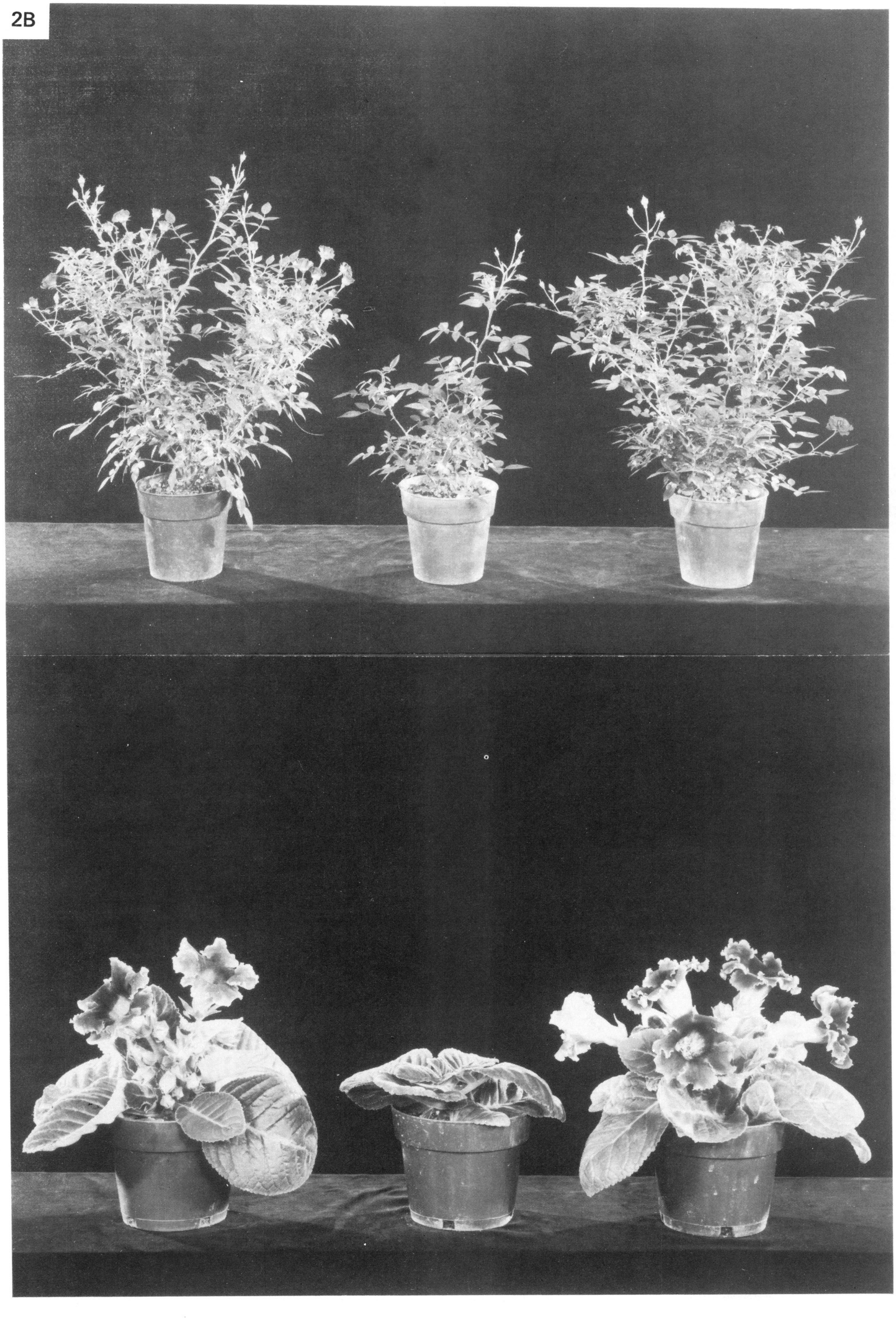


Fig. 2. Plants of (A) *Hydrangea* (upper) and *Juniperus* (lower); (B) *Rosa* (upper) and *Sinningia* (lower) treated with: left to right, Natural days (ND) + 16 hr 22,000 Lx Low-Pressure Sodium (0800-2400), ND, ND + 16 hr 17,000 lx High-Pressure Sodium (0800-2400).

2B



equally effective on most of the species tested. This supported the conclusion that light quality was not as much a consideration as total radiation (energy) for the growth of plants.

The pigment systems that regulate phototropism and photomorphogenesis absorb light at 589 nm poorly but a regulatory effect was exerted when such light was given over 8 or 16 hr daily. The low intensity natural light augmented whatever deficiencies there were in the spectra of the artificial light sources. Thus, deficiencies in the red, blue, and far-red regions of the spectrum became critical only under carefully defined conditions. Traditional methods of identifying the photoperiodic responses of plants use supplemental lighting of an energy level and duration which is assumed to regulate phytochrome but not chlorophyll activity. Low-intensity INC was our preferred light source for establishment of photoperiodic control of the growth of long and short day plants.

The results in this paper were extremely difficult to relate to other published articles on the subject. Other reports (2, 7, 8, 14, 15, 21) have demonstrated the benefits of supplemental lighting in greenhouses on a wide range of horticultural and agronomic crop plants. However, the lighting facilities were so different from ours that it was impossible to compare growth responses from their tests with our data reported here. None utilized a long day (ND + 8 hr INC) as the basis for comparison of the growth responses and none compared the relative effectiveness of 2 light sources of equal energies. The traditional approach is to supplement the available sunlight and artificially lengthen the day to 12 or 16 hr. The experiments in this report utilized light treatments that had definite relationships to each other as to duration (8-16 hr), time (day, day into night and night) and amount of energy (21 or 42 W/m^2). These energy levels were selected after detailed studies in growth chambers with *Petunia* and *Lactuca* plants (10) and separated the benefits of a sole light source (HPS, LPS, or cool white fluorescent, CWF) from those of a supplemental light source in a greenhouse with available sunlight.

The supplemental lighting treatments reported in this paper created an environment in which many plants grew as if they were photoperiodically responsive. We actually created a light environment that was near optimum for rapid but not maximum growth of our plants. Supplemental lighting with HPS and LPS in greenhouses produced plants with intense, deep-green leaves, rapidly extending stems, many side branches, and accelerated flowering. Similar plants were produced in greenhouses with natural light only for a few weeks in spring and fall. HPS and LPS supplemental lighting can help extend the near optimum growing environment throughout most of the year in greenhouses.

We believe that most light sources can be used to create a near optimum growing environment when installed to give 21 to 42 W/m^2 in the 400-700 nm region. HPS and LPS are the most efficient supplementary lighting sources currently available when evaluated on lumens/watt or irradiance per input watt (6). Any lamp, as long as it produces radiation in the 400-700 nm region, can readily be utilized to supplement inadequate lighting in greenhouses once the conversion factors are calculated.

LPS or other narrow spectrum light sources may not be as effective as HPS or other broad spectrum light sources when the natural light conditions in the greenhouse (intensity, quality, duration) are less than the winter light conditions at Beltsville, Maryland. As shown in our growth chamber studies (10), HPS or CWF can be used as a sole light source for growing many plant species. For the most prompt and rapid growth, however, lighting systems combining HPS and CWF with INC were more effective than any sole source evaluated. *Lactuca* and *Impatiens* plants did not develop their typical green leaves and compact growth habit with LPS as the sole light source. However, chlorophyll was formed and node elongation was suppressed with the addition of INC to LPS.

In woody plants supplemental lighting should delay the onset of dormancy and permit continued vegetative growth through the winter. Differences among species in light regulated growth systems were evident. *Buxus, Hydrangea* (Fig. 2A), *Ilex, Juniperus* (Fig. 2A), *Rosa* (Fig. 2B), and *Thuja* continued to grow throughout the winter. The *Hydrangea* plants remained vegetative when lighted with supplemental HPS or LPS and initiated resting flower buds under natural days or/and LD (or with INC), and resting vegetative buds under SD. The *Chamaecyparis* plants continued to develop dense, compact, highly branched shoots, typical of the species when grown during the summer in the greenhouse or out-of-doors. *Camellia, Carya,* and *Taxus,* did not grow in any of our environments; whereas plants of *Tsuga* grew slowly but at equal rates under all treatments.

We thus can use supplemental light (INC) to delay the flowering of short day plants or to delay the winter dormancy of woody plants. We can accomplish this by extension of natural daylengths or by interruption of dark periods with low intensity INC (near equal R-FR) or high intensity HPS and LPS (589 nm peak). The onset of dormancy can be delayed easily only with a few woody species (9, 11, 13, 18, 20) and the INC light source works best as a night interruption. Supplemental lighting with HPS and LPS regulated the growth of some woody plant species, such as *Buxus, Chamaecyparis,* and *Juniper,* while most deciduous trees went dormant even with 16 hrs of 42 W/m^2. We were apparently not meeting their light requirements for sustained and continuous growth. Delay of dormancy will become more important in the future when a wide range of woody plants are propagated from single cells or callus tissues.

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The Effects of Node Position, Shoot Vigor, and Strain on 'Delicious' Apple Spur Development[1]

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Additional index words. 6-benzylamino purine, *Malus domestica*

Abstract. **Bud weight, and spur number, length, and fruitfulness were measured in shoots of 'Delicious' apple (*Malus domestica* Borkh.). In 2-, 3-, and 4-year-old wood, spur number, length, and fruitfulness were greater at the subapical nodes than at the basal nodes of the shoot. In dormant 1-year-old shoots, bud weight was affected by strain, node, position, and vigor. Axillary buds were largest in the apical portion of standard 'Delicious' shoots and in the basal portion of spur-types. In extremely vigorous shoots of 'Gardner Delicious' basal buds did not grow at the beginning of the second growing season unless treated with 6-benzylamino purine (BA), which induced normal spurs.**

'Delicious' is the most widely grown apple cultivar in the United States. However, many difficulties exist in managing this cultivar. Problems in pollination, climatic adaptability, and excessive vigor may limit yields (15, 16, 18). Excessive vigor leads to delayed bearing. Attempts at correcting this problem by training and pruning have been only moderately successful (5, 18). 'Delicious' trees are also susceptible to the dead spur (DS) disorder which causes large sections of the scaffold limbs to be barren of spurs (9). DS occurs in young trees which appear to be receiving adequate light and fertilizer. Frequently this type of growth occurs in young plantings in New York. The purpose of this study was to investigate the effects of cultivar, vigor, and node position on spur development in 'Delicious'.

Materials and Methods

Spur development in 'Starkrimson Delicious'. Trees used were 7 years old on Malling-Merton (MM) 106 rootstocks. They were planted in a commercial orchard in Belchertown, Massachusetts, and had a history of poor cropping. On each of 18 trees, a bearing 4-year-old scaffold limb was selected for study. Limbs selected were carrying a moderate crop, and bore no pruning cuts. Each season's extension growth was divided into 10 sections of equal length. In mid-July, spur number, spur length, and fruit per spur were determined in each section. Rosettes and short shoots of less than 6 cm extension growth per year of age were classified as spurs.

The relationships between position and spur number, length, and fruit per spur were analyzed statistically using stepwise polynomial regression (4). The regression analysis was terminated when the F-value of an additional polynomial term was less than 10.83 (significant at 0.1% level with 1 and 120 degrees of freedom).

Spur development in greenhouse-grown 'Imperial Delicious'. Three-year-old trees on Malling (M) 7a were used in this study. Nine trees were grown in 19 liter containers in 1 soil:1 sand:3 peat:3 vermiculite. Trees were fertilized weekly with soluble 20N–9P–16K throughout the growing season. The dormant trees were pruned to 3 shoots in March. One shoot was staked vertically and the others bent to 45^{o} from vertical. The trees were spaced about 0.5 m x 0.6 m in the greenhouse to avoid shading. When shoot extension ceased, the growth made at each node in 2-year wood was measured in the limbs bent to 45^{o}. To tabulate these data, each shoot was divided into 5 equal sections and mean values were determined for each section.

Shoot vigor and axillary bud growth. One-year-old shoots of 'Gardner Delicious' on M 7 grown at the Cornell Orchard, Ithaca, N.Y., were used in this study. Three shoots were harvested from each of ten 17-year-old trees at monthly intervals from January until May. The shoots represented weak, moderately vigorous, and excessively vigorous growth (about 25, 50, and 100 cm, respectively). Shoots with 2 flushes of growth were avoided. Each shoot was dried and divided into 10 sections of equal length. Axillary buds from each section of the shoot were weighed at each date.

Effects of dormant applications of BA on spur development. Four 1-year-old shoots 38 to 123 cm in length were selected on each of 17 'Gardner Delicious' trees. Prior to budburst, the basal half of each shoot was treated with BA dissolved in a 5% dimethylsulfoxide (DMSO), 45% methanol, 50% water mixture (2). BA concentrations used were 0, 200, 1000, and 5000 ppm. Treatments were applied with a brush on both April 9 and 23. Shoots were harvested in October and spur number, and spur and leaf dry wt were determined in the upper and lower halves of each shoot.

[1]Received for publication April 4, 1979.
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