Nitrogen Fertilization and HPS Supplementary Lighting Influence Vegetable Transplant Production. I. Transplant Growth

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Abstract. This experiment was initiated to determine the effects of supplementary lighting of 100 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ (PAR) in combination with four N rates (100, 200, 300, and 400 mg N/liter) on growth of celery (*Apium graveolens* L.), lettuce (*Lactuca sativa* L.), broccoli (*Brassica oleracea* italica L.), and tomato (*Lycopersicon esculentum* Mill.) transplants in multicellular trays. Supplementary lighting, as compared with natural light alone, increased shoot dry weight of celery, lettuce, broccoli, and tomato transplants by 22%, 40%, 19%, and 24%, and root dry weight by 97%, 42%, 38%, and 21%, respectively. It also increased the percentage of shoot dry matter of broccoli and tomato, leaf area of lettuce and broccoli, and root : shoot dry weight ratio (RSDWR) of celery and broccoli. Compared with 100 mg N/liter, a N rate of 400 mg·liter⁻¹ increased the shoot dry weight of celery, lettuce, broccoli, and tomato transplants by 37%, 38%, 61%, and 38%, respectively. High N fertilization accelerated shoot growth at the expense of root growth, except for tomato where a 16% increase of root dry weight was observed. High N also reduced percentage of shoot dry matter. Supplementary lighting appears to be a promising technique when used in combination with high N rates to improve the production of high quality transplants, particularly those sown early.

According to Tosi and Tesi (1987), transplants with optimal vegetative development can better withstand the stresses caused by the field environment, pests, and diseases following transplanting. Specific characteristics are claimed to be necessary to lessen transplant shock and obtain maximum yield at harvest. For example, stem diameter of celery seedlings (Dufault, 1985) and of tomato transplants (Liptay et al., 1981) is an indication of their vigor and, according to Liptay et al. (1981), the accumulated reserves in tomato transplant stems enhance early fruiting.

High N levels used during celery transplant production have been found beneficial to yield of mature plants (Tremblay et al., 1987). In a subsequent study (Tremblay and Gosselin, 1989), a yield increase was obtained with high N only when 50% of it was provided as urea. However, urea generally did not have much influence on vegetable transplant vegetative characteristics (Tremblay and Senécal, 1990). High N levels are known to favor shoot rather than root growth. However, transplants with well-developed root systems are reported to recover more quickly from transplant shock (Weston and Zandstra, 1986).

The use of supplementary lighting may lessen the undesirable effects of high N on vegetative characteristics. An experiment on this topic conducted in Winter 1988 on lettuce and tomato transplants (Masson et al., 1990) confirmed that high rates of N fertilization increased shoot growth more than root growth. Supplementary lighting promoted a balance between shoot and root development and increased the percentage of shoot dry matter.

The objectives of our experiments were to: a) determine the effects of supplementary lighting and N fertilization on the growth

of celery, lettuce, broccoli, and tomato transplants during a normal production period; b) clarify the interactions of the two factors; and c) test the replicability of the treatments effects over time by means of two seeding dates for lettuce, and three for broccoli and tomato.

Material and Methods

Plant material and growing conditions

Plant material used included 'Florida 683' celery, 'Ithaca' lettuce, 'Premium Crop' broccoli, and 'Springset' tomato. Seeds were sown in multicell flats (Sutton plug trays #288 for celery and lettuce, and #128 for broccoli and tomato) using a peat-based substrate (Seeding Mix, Les tourbières Premier Ltée, Rivière-du-Loup, Quebec). The flats were placed in a polyethylene greenhouse, located at Laval Univ. (Quebec City). Tomato flats were placed on a table with heating cables that maintained the substrate at 24C. The seedlings were thinned to one per cell when emergence was completed, and treatments were initiated at this stage. An early and a late seeding were performed for lettuce while early, midseason, and late seedlings of broccoli and tomato were conducted. Celery was sown only once. Table 1 gives the dates for various operations. Overhead fertigation was performed twice daily to partial runoff. Seedlings were watered 1 day·week⁻¹ with tap water to prevent an increase of salinity in the medium (Kratky and Mishima, 1981). Mean air temperature was maintained between 20 and 23C (day) and 17.0 and 18.0C (night) for the different species and seedlings during the course of the experiment.

Treatments

The transplants were under natural light (control) or under supplementary lighting. The latter was provided by 400-W HPS

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Abbreviations: LAR, leaf area ratio; RSDWR, root : shoot dry weight ratio; SLA, specific leaf area.

Table 1. Seeding schedule, treatment initiation, and growth measurement dates of celery, lettuce, broccoli, and tomato transplants grown in multicellular trays under various supplementary lighting and N fertilization regimes.

Species	Sowing	Seeding date	Treatment initiation	Growth measures
Celery	Midseason	30 Mar.	7 Apr.	16 May
Lettuce	Early	21 Apr.	25 Apr.	16 May
	Late	6 May	10 May	29 May
Broccoli	Early	18 Apr.	22 Apr.	16 May
	Midseason	25 Apr.	29 Apr.	23 May
	Late	11 May	16 May	6 June
Tomato	Early	21 Apr.	30 Apr.	24 May
	Midseason	3 May	12 May	2 June
	Late	16 May	24 May	15 June

lights (No. 400-SO-SHP-120-Solux Lumiponic, Boisbriand, Quebec) giving a photosynthetic photon flux density (PPFD) of $100 \pm s = 10 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ photosynthetically active radiation (PAR) (72 measures) at the level of the multicell flats using a LI-COR LI-185 photometer equipped with a LI-COR LI-190SB (LI-COR, Lincoln, Neb.) quantum sensor. The lights were turned on before sunrise and off at sunset so as to have a 16-h photoperiod. The starting time for the lighting was changed once a week in relation to the time of sunset. The lights were lit during the day when natural PPFD was $<250 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$. Table 2 presents available natural and artificial light energy and the number of hours of lighting per day for each species and seeding. Shade from the greenhouse structure caused a 60% loss of transmission. As recommended by Thimijan and Heins (1983), the data were also expressed as total natural and artificial light energy on a 24-h basis.

The fertilization treatments consisted of four nutrient solutions with N concentrations of 100, 200, 300, and 400 mg-liter⁻¹.

Nitrogen was provided according to a ratio of N-NO₃:N-NH₄:N-Urea of 2:1:2. All the nutrient solutions had the same concentrations (mg-liter⁻¹) of P (150), K (250), Ca (50), Mg (20), Fe (2), Mn (0.5), Cu (0.03), B (2.5), Zn (0.05), and Mo (0.02). The pH of the nutrient solution was adjusted to 6.0 using NaOH. The electrical conductivity was 1.89, 2.03, 2.16, and 2.36 mS·cm⁻¹, respectively, for 100, 200, 300, and 400 mg N/liter.

Experimental design, characteristics measured, and statistical analysis

The greenhouse was divided into four experimental blocks placed east-west. Each block was divided into two plots separated by curtains, where light treatments were divided at random. The curtains were drawn from 0800 to 1730 HR. For each species and seeding date, four multicell flats (subplots) were placed under each light treatment. A row of plants on the sides of the trays served as guard rows. The N fertilization treatments and seedlings were divided at random and the flats were regularly randomized within their lighting sections. The experimental units, made up of one multicell flat, were distributed in the greenhouse according to a split-plot design, with the lighting treatments as the main plots and the N fertilization treatments and seeding dates combination as subplots. Since celery was sown only once, the subplots contained only fertilization treatments.

The analysis of variance was performed for each species according to a split-plot design with the lighting treatment (two levels) as the main plots. The subplots for celery contained the N treatment (four levels), for lettuce it contained the N treatment and seeding date combination (four levels of N and two seeding dates) and for tomato and broccoli (four levels of N and three seeding dates). The experiment was done with four replications

Table 2. Contribution of natural and supplementary lighting to the light integral (PAR) received in the greenhouse by transplants for the various sowings.

Sowing	Lighting level	Lamp use (h·day ⁻¹)	Natural light integral (PAR) (W·m ⁻² ·day ⁻¹)	Supplemental light integral (PAR) (W·m ⁻² ·day ⁻¹)	Total light integral (PAR) (W·m ⁻² ·day ⁻¹)	Mean light integral (24-h basis) (W·m ⁻² ·h ⁻¹)	Increase attributed to suppl. lighting (%)
<i>Celery</i>							
Midseason	Natural	0	1094	0	1094	45.6	---
Midseason	Supplemented	12.5	1094	250	1344	56.0	22.8
<i>Lettuce</i>							
Early	Natural	0	1313	0	1313	54.7	---
Late	Natural	0	1365	0	1365	56.9	---
Early	Supplemented	11.6	1313	232	1545	64.4	17.7
Late	Supplemented	11.3	1365	226	1591	66.3	16.6
<i>Broccoli</i>							
Early	Natural	0	1208	0	1208	50.3	---
Midseason	Natural	0	1400	0	1400	58.3	---
Late	Natural	0	1433	0	1433	59.7	---
Early	Supplemented	11.8	1208	236	1444	60.2	19.5
Midseason	Supplemented	10.5	1400	210	1610	67.1	15.0
Late	Supplemented	9.6	1433	192	1625	67.7	13.4
<i>Tomato</i>							
Early	Natural	0	1337	0	1337	55.7	---
Midseason	Natural	0	1412	0	1412	58.8	---
Late	Natural	0	1428	0	1428	59.5	---
Early	Supplemented	11.5	1337	230	1567	65.3	17.2
Midseason	Supplemented	9.9	1412	198	1610	67.1	14.0
Late	Supplemented	9.7	1428	194	1622	67.6	13.6

for all species. The Bartlett test was used ($P \leq 0.01$) to verify the homogeneity of variance.

When transplant stage was reached (Table 1), 15 celery and lettuce plants and 10 broccoli and tomato plants per experimental unit were sampled for growth measurements. The fresh and oven-dried (70C) weights were determined for leaves without petioles, stems with petioles, and roots previously washed. Leaf area was measured using a LI-COR LI-3000 (LI-COR) area meter. LAR was calculated by dividing leaf area by shoot (including stem, petiole, and leaf blade) dry weight. SLA (leaf blade area/leaf blade dry weight), RSDWR, and the percentage of shoot dry matter were also calculated.

Since the interactions between seeding date and the lighting and fertilization treatments are rare or marginally significant ($P \leq 0.05$), we have combined the data and have only reported the averages for the three seedlings of tomato and broccoli. For lettuce, the more important interactions of treatments with seeding date are discussed in the text.

Results and Discussion

Shoot dry weight. Supplementary lighting significantly increased shoot dry weight of celery, lettuce, broccoli, and tomato by 22%, 40%, 19%, and 24%, respectively (Tables 3, 4, 5, and 6). Dry weight accumulated in celery stalks but not in the leaf blade; for broccoli and tomato, both variables increased. According to Liptay et al. (1981), the reserves accumulated in tomato transplant stems promote earliness. Stem dry weight can be considered a good indicator of the radial growth of the transplants' base, which is evidence of the young plant's vigor (Dufault, 1985; Liptay et al., 1981).

High rates of N fertilization also increased shoot dry weight for all species (Tables 3, 4, 5, and 6). Nitrogen at 400 mg-liter⁻¹ increased celery, lettuce, broccoli, and tomato shoot dry weight by 37%, 38%, 61%, and 38%, respectively, compared with N at 100 mg-liter⁻¹. For celery and broccoli, shoot dry weight increased curvilinearly in relation to N, whereas a linear response was obtained for tomato. Similar results for tomato were reported by Weston and Zandstra (1989). With celery, the increase of shoot dry weight with N rates was linear under natural light, but a plateau was reached under supplementary lighting at 300 mg N/liter. Tremblay et al. (1987) observed higher biomass at a rate of 400 mg N/liter for celery transplants than at rates of 200 and 600 mg-liter⁻¹. In our study, 100 mg N/liter limited shoot growth under natural and supplementary lighting.

Response of lettuce shoot dry weight to N rates was complex but, under supplementary lighting, the highest shoot dry weight was obtained with 400 mg N/liter.

Percentage of shoot dry matter. Supplementary lighting improved the percentage of shoot dry matter for broccoli, tomato (Tables 5 and 6), and lettuce (data not shown) but not for celery (Table 3). Tesi and Tallarico (1984) reported that an increase in percentage of shoot dry matter improves cold resistance and that a good tomato transplant should have > 10% dry matter. Increasing the N rate decreased the percentage of shoot dry matter in all species (Tables 3, 4, 5, and 6), with the lowest percentages obtained at highest level of N fertilization. A similar response was previously reported for celery, lettuce, broccoli, and pepper (Tremblay and Sénécal, 1988; Tremblay et al., 1987). Transplants overfertilized with N show an increase in succulence and are easily broken when transplanted (Kratky and Mishima, 1981).

Leaf area, SLA, and LAR. Leaf area for lettuce and broccoli increased under supplementary lighting (Tables 4 and 5), but no effect was detected for celery and tomato (Tables 3 and 6). Supplementary lighting enhanced leaf area development for early tomato seeding only (data not shown). According to Boivin et al. (1986), leaf area is a poor indicator of the effect of light treatments on growth of tomato transplants. Supplementary lighting lowered the SLA of celery, broccoli, and tomato (Tables 3, 5, and 6), but not that of lettuce (Table 4). A low SLA is desirable since it is associated with greater leaf thickness. Leaf anatomy is changed by an increase in light energy (Salisbury and Ross, 1985), as is the case for the amount of chlorophyll and the chloroplasts (Björkman, 1981). Leaves adapt to high amounts of radiation, and one can generally observe an elongation of the palisade layer or the addition of a second layer of cells. Under high PPFD, the palisade layer cells generally elongate so that the leaves are thicker and a decrease in SLA is observed. A low SLA may make transplants more resistant to transplant shock. The increase in natural light energy associated with later seeding seemed to lessen the effect of supplementary lighting on the SLA of broccoli (data not shown) but not that of tomato.

The increase in leaf area with N fertilization (Tables 3, 4, 5, and 6) is in agreement with several studies (Dufault, 1985, 1986; Tremblay and Sénécal, 1988; Weston and Zandstra, 1989). Lettuce, broccoli, and tomato SLA increased with N rate in a curvilinear manner (Tables 4, 5, and 6), but celery was not

Table 3. Effect of supplementary lighting (100 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$; PAR) and four N levels on celery transplant growth.

Treatments		Dry wt (mg/plant)				Shoot dry matter (%)	Leaf area (cm ² /plant)	SLA (cm ² ·mg ⁻¹)	LAR (cm ² ·mg ⁻¹)	RSDWR
Light	N (mg·liter ⁻¹)	Shoot	Stem	Leaf	Root					
Natural	100	123	52	71	12	8.5	31.4	0.44	0.25	0.10
	200	134	58	76	8	8.0	33.5	0.44	0.25	0.06
	300	133	58	75	7	7.7	32.8	0.44	0.25	0.05
	400	146	65	81	9	7.7	35.7	0.44	0.24	0.06
Supplementary	100	116	47	69	27	8.8	27.2	0.40	0.24	0.23
	200	171	74	97	18	9.5	36.4	0.37	0.21	0.11
	300	183	81	102	14	8.0	41.6	0.41	0.23	0.08
	400	182	80	102	12	8.1	41.0	0.40	0.22	0.06
Significance ^a										
Nitrogen		L***,Q*	L***,Q*	L***,Q*	L***	L**	L***	NS	NS	L***,Q***
Light		*	*	NS	*	NS	NS	**	**	*
Nitrogen $\times$ light		L**,Q*	L*,Q*	L**,Q*	L**	NS	L**,Q*	NS	NS	L***

^aLinear (L) or quadratic (Q) effects significant at $P = 0.05$ (*), 0.01 (**), or 0.001 (***) or nonsignificant (NS)

Table 4. Effect of supplementary lighting (100 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$; PAR) and four N levels on lettuce transplant growth (averages of two seeding dates).

Treatments		Dry wt (mg/plant)		Shoot dry matter (%)	Leaf area (cm^2/plant)	SLA ($\text{cm}^2\cdot\text{mg}^{-1}$)	RSDWR
Light	N ($\text{mg}\cdot\text{liter}^{-1}$)	Shoot	Root ^z				
Natural	100	85	9	6.0	34.2	0.41	0.11
	200	91	7	5.4	38.9	0.43	0.08
	300	99	8	5.2	43.9	0.45	0.08
	400	97	6	5.0	43.3	0.45	0.07
Supplementary	100	97	13	6.5	35.7	0.37	0.13
	200	135	11	5.5	54.3	0.41	0.08
	300	136	11	5.1	58.0	0.43	0.08
	400	153	7	5.2	63.4	0.42	0.05
Significance ^y							
Nitrogen		L***,Q**,C*	L***	L***,Q***	L***,Q**	L***,Q*	L***,Q*
Light		**	*	NS	**	NS	NS
Nitrogen $\times$ light		L***,C**	NS	Q*	L***,Q*,C*	NS	L**

^zOne transformation, $(Y + 0.5)^{1/2}$, was necessary for this characteristic; the raw data are listed in the table.

^yLinear (L), quadratic (Q) or cubic (C) effects significant at $P = 0.05$ (*), 0.01 (**), or 0.001 (***) or nonsignificant (NS).

Table 5. Effect of supplementary lighting (100 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$; PAR) and four N levels on broccoli transplant growth (averages of three seeding dates).

Treatments		Dry wt (mg/plant)				Shoot dry matter (%)	Leaf area (cm^2/plant)	SLA ($\text{cm}^2\cdot\text{mg}^{-1}$)	LAR ($\text{cm}^2\cdot\text{mg}^{-1}$)	RSDWR
Light	N ($\text{mg}\cdot\text{liter}^{-1}$)	Shoot	Stem	Leaf	Root					
Natural	100	179	65	114	40	11.4	32.1	0.28	0.18	0.23
	200	224	84	139	35	9.4	45.4	0.33	0.20	0.15
	300	269	99	170	33	8.9	56.0	0.33	0.21	0.12
	400	282	103	179	31	8.8	58.1	0.33	0.21	0.11
Supplementary	100	209	73	136	53	12.6	32.1	0.24	0.15	0.25
	200	280	103	177	50	10.1	50.2	0.28	0.18	0.18
	300	302	112	190	46	9.4	57.5	0.30	0.19	0.15
	400	344	125	219	43	9.3	66.3	0.30	0.19	0.12
Significance ^z										
Nitrogen		L***,Q***	L***,Q***	L***	L***	L***,Q***,C*	L***,Q***	L***,Q***	L***,Q***	L***,Q***
Light		*	*	**	***	*	*	**	**	**
Nitrogen $\times$ light		NS	NS	NS	NS	L*	L*,C*	L*	L*	NS

^zLinear (L), quadratic (Q), or cubic (C) effects significant at $P = 0.05$ (*), 0.01 (**), or 0.001 (***) or nonsignificant (NS).

Table 6. Effect of supplementary lighting (100 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$; PAR) and four N levels on tomato transplant growth (averages of three seeding dates).

Treatments		Dry wt (mg/plant)				Shoot dry matter (%)	Leaf area (cm^2/plant)	SLA ($\text{cm}^2\cdot\text{mg}^{-1}$)	LAR ($\text{cm}^2\cdot\text{mg}^{-1}$)	RSDWF
Light	N ($\text{mg}\cdot\text{liter}^{-1}$)	Shoot	Stem	Leaf	Root					
Natural	100	233	100	133	35	8.2	45.8	0.34	0.20	0.15
	200	273	130	144	39	6.6	65.5	0.45	0.24	0.14
	300	303	141	162	36	6.3	77.6	0.48	0.26	0.12
	400	336	149	187	41	6.5	84.3	0.45	0.25	0.12
Supplementary	100	294	124	170	40	9.8	45.0	0.27	0.16	0.14
	200	363	162	201	48	7.7	74.1	0.37	0.20	0.13
	300	373	171	202	48	7.1	83.8	0.42	0.23	0.13
	400	393	177	216	46	7.1	90.8	0.42	0.23	0.12
Significance ^z										
Nitrogen		L***	L***,Q**	L***	L*	L***,Q***	L***,Q***	L***,Q***	L***,Q***	L***
Light		**	*	**	**	*	NS	*	*	NS
Nitrogen $\times$ light		NS	NS	NS	NS	L**	NS	L*	NS	NS

^zLinear (L) or quadratic (Q) effects significant at $P = 0.05$ (*), 0.01 (**), or 0.001 (***) or nonsignificant (NS).

affected (Table 3). For broccoli, the effects of N and supplementary lighting on the SLA were greater with early seedlings (data not shown). For tomato, the increase in SLA with N fertilization was more pronounced under supplementary lighting.

Supplementary lighting reduced LAR in celery, broccoli, and tomato (Tables 3, 5, and 6). For broccoli, the effect of supplementary lighting on LAR was less in the late seedlings, contrary to the observations for tomato (data not shown). Boivin et al. (1986) observed a lowering of LAR in greenhouse tomato transplants placed under increasing PPFD.

LAR of broccoli and tomato increased curvilinearly with N rate. Tremblay and Senécal (1988) reported increased LAR for broccoli and green pepper when plants were grown with 350 instead of 150 mg N/liter. With broccoli, the response of LAR to N rate was greater without supplementary lighting (Table 5). The LAR and SLA of broccoli and tomato changed in a very similar way according to the lighting and fertilization treatments, thus indicating a similar response of leaves and stems. The effect of supplementary lighting and N on the LAR of tomato plants increased the later they were sown (data not shown).

Root dry weight and RSDWR Root dry weight of all species increased with supplementary lighting (Tables 3, 4, 5, and 6) by 97%, 42%, 38%, and 21% for celery, lettuce, broccoli, and tomato, respectively. According to Weston and Zandstra (1986), transplants with a well-developed root system recover better in the field.

Increasing N fertilization decreased celery, lettuce, and broccoli root dry weight (Tables 3, 4, and 5). Tomato plants, however, showed a linear increase (Table 6), as noted by Weston and Zandstra (1989). Tomato root dry weight was 16% higher with 400 than with 100 mg N/liter. Tremblay and Senécal (1988) reported a decrease in root weights of celery, lettuce, and broccoli caused by high rates of N fertilization.

The RSDWR of celery and broccoli was increased by supplementary lighting (Tables 3 and 5). However, lighting did not affect this relation for lettuce and tomato (Tables 4 and 6). RSDWR decreased curvilinearly in relation to N rate in celery, lettuce, and broccoli but linearly for tomato (Tables 3-6). Decreases in RSDWR caused by high N rates have been reported for several species (Dufault, 1985; Tremblay and Senécal, 1988; Tremblay et al., 1987; Weston and Zandstra, 1989). For celery and lettuce, this decrease was more evident under supplementary lighting.

In summary, the use of supplementary lighting (HPS) of 100 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ (PAR) on seedlings during transplant production promoted balanced growth. Supplementary lighting also improved shoot and root dry weights of all species and it can be used in combination with high N fertilization for most of the species tested to obtain vigorous transplants, with acceptable levels of dry matter percentage. Supplementary lighting can be considered a promising technique to hasten production of good quality transplants in northern latitudes, particularly for early seeding dates. Nitrogen at 100 mg-liter⁻¹ limited growth of all the species. Rates of 300 to 400 mg N/liter optimized growth

of the transplants under natural light, while 400 mg N/liter was generally optimal under supplementary lighting or when sowing was late. Since such high N levels may be detrimental to transplant survival under field conditions, it is therefore necessary to verify the consequences of this treatment in the field.

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