Nutrient Requirements for Lettuce Transplants Using a Floatation Irrigation System. I. Phosphorus

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Abstract. Several levels of P were supplied via floatation irrigation to ‘South Bay’ lettuce (*Lactuca sativa* L.) transplants to determine the optimum P concentration necessary. Plants were propagated by floating flats (ebb and flow system) in a nutrient solution containing P at either 0, 15, 30, 45, or 60 mg·L⁻¹ in summer and fall experiments, and either 0, 15, 30, 60, or 90 mg·L⁻¹ P in a factorial combination with 60 or 100 mg·L⁻¹ N in a winter experiment. Adding more than 15 mg·L⁻¹ P had minimal effect on growth. Transplants produced with 0 P grew poorly, regardless of the level of N applied. Nitrogen at 100 mg·L⁻¹ improved the response of shoot growth to any level of P, but adversely affected root growth compared with N applied at 60 mg·L⁻¹. In general, relative growth rate was improved, while net assimilation rate was reduced at all levels of P. High-quality transplants had a root to shoot ratio of about 0.25, total root lengths between 276 and 306 cm, and total root area between 26 and 30 cm² in a 10.9-cm³ cell volume. Only 30% of the plants produced without P could be pulled from the transplant flats, whereas 90% could be pulled when P was added. Pretransplant P hastened maturity and increased lettuce head weight at harvest in the field. This work suggested that at least 15 mg·L⁻¹ P, supplied via floatation irrigation to a peat + vermiculite mix, was required to produce a transplant with sufficient roots for ease of pulling, rapid field establishment, and earlier harvest.

Vegetable transplants grown in plug cells require careful management of fertilizers (Dufault and Waters, 1985; Weston, 1988) because of limited cell volume and high seedling densities. Concentrations of essential plant nutrients in the media are frequently insufficient to sustain plant growth, given frequent irrigation (Garton and Widders, 1990). Production of vigorous seedlings is a prerequisite for successful vegetable production, especially in lettuce, where the period of containerized growth comprises up to 30% of the entire crop cycle (Cantliffe and Karchi, 1992). Improved

nutrient regimes would contribute to efficient development of high-quality transplants (Tremblay and Senécal, 1988).

The role of P in transplant growth has been investigated in a number of vegetable crops. Increasing the P concentration from 5 to 125 mg·L⁻¹ increased celery (*Apium graveoleus* L.) transplant stem diameter and height, shoot and root weight, and leaf area (Dufault, 1985). Increasing P from 5 to 45 mg·L⁻¹ increased tomato (*Lycopersicon esculentum* Mill.) transplant height, stem diameter, leaf number, leaf area, and fresh shoot weight, but not shoot or root dry weight (Melton and Dufault, 1991). Dufault and Schultheis (1994) reported that increasing P from 5 to 45 mg·L⁻¹ increased fresh and dry shoot weight, leaf area, and leaf count of pepper (*Capsicum annuum* L.) transplants, when combined with 75 or 225 mg·L⁻¹ N, but not with 25 mg·L⁻¹ N. Phosphorus at 5, 15, or 45 mg·L⁻¹ did not influence root dry weight.

Data are lacking on the response of roots and shoots of lettuce transplants to frequent P applications using a floatation irrigation system. In this system, nutrients can be supplied with each irrigation by floating flats directly in the nutrient solution for a period of time then removing the water (ebb and flow). This system of irrigation is preferred to overhead irrigation because it is less conducive to promoting spread of foliar pathogens. Growers using this system have had problems produc-

ing lettuce transplants with sufficient roots in a tray cell to allow their removal from the flat, particularly during late fall to early spring (i.e., winter season) production in the greenhouses. The reasons for this are unknown; therefore, in the present investigation we determined the P concentrations, supplied via floatation irrigation, required for production of easy-to-pull transplants which would establish rapidly in the field. We also investigated the interaction of N fertility with P fertility and transplant growth during the winter season wherein temperature and light conditions are reduced.

Materials and Methods

Greenhouse experiments. ‘South Bay’ lettuce transplants were grown in a glass greenhouse at the Univ. of Florida, Gainesville, using Speedling® (Sun City, Fla.) styrofoam planter flats, model F392A [392 cells of 1.9 × 1.9 × 1.9 cm; 10.9 cm³ (length × width × depth; volume)]. The medium was a 1 peat : 2 vermiculite : 1 styrofoam bead mix (v/v), with AquaGro wetting agent (Aquatrols, Cherry Hill, N.J.) at 0.2 kg·m⁻³. Three experiments were conducted (Table 1). A commercial media (Speedling) with added P and N was used in the first experiment. In order to avoid misinterpretation of results, the media was adjusted with no added N or P. The plants were grown with natural photoperiod extended to 16 h by 1000-W, high-pressure sodium lamps [250 μmol·m⁻²·s⁻¹ photosynthetic photon flux PPF]. A record of cloud cover was kept as an indication of evaporative demand. Both greenhouse air temperature just above the plant canopy and media temperatures were recorded by a Series 3020T Datalogger (Electronic Controls Design, Mulino, Ore.). The flats were seeded, then covered with a thin layer of vermiculite, overhead irrigated sufficiently to moisten the vermiculite, and transferred to a controlled temperature room at 20 °C for germination. After 48 h, flats were returned to the greenhouse.

Plants in Expts. 1 and 2 were irrigated (fertigated) every 2 to 4 d, depending on water needs, by floating flats until field capacity was reached in nutrient solution containing P at 0, 15, 30, 45, or 60 mg·L⁻¹ as Na₂HPO₄. The flats were floated in plastic-lined tubs; the nutrient solution was drained and stored in tanks and/or re-used during a 1-week period afterwards, then new solutions were made. The pH and N, P, and K levels were monitored during this period. Other nutrients were supplied at equivalent rates to all plants and consisted of (in mg·L⁻¹) 100 N, 30 K, 100 Ca. The solution also contained Mg, S, B, Cu, Cl, Mo, and Zn as half-strength Hoagland’s solution (Hoagland and Arnon, 1950). In Expt. 2, the Ca concentration was reduced from 100 to 30 mg·L⁻¹. Expt. 1 was conducted in the summer in the greenhouse with average daily maximum media temperatures of 31 °C and daily maximum of 22 °C. Expt. 2 was conducted during the fall in the greenhouse with average daily maximum media temperature of 33 °C and daily minimum of 26 °C.

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Table 1. Sowing schedule and initial media chemical analysis for the three experiments with lettuce transplants and transplanting schedule for Expt. 1 and 2.

Expt. no.	Sowing date	pH	Media test ²					
			EC (dS·m ⁻¹)	NO ₃ -N	P	K (mg·kg ⁻¹)	Ca	Mg
1	17 June 1993	4.7	0.9	1.3	12.4	14.6	14.2	11.6
2	18 Sept. 1995	4.5	0.6	0.0	0.6	46.2	6.3	22.2
3	31 Jan. 1996	5.2	0.2	0.3	0.4	24.4	0.6	5.8

Expt. no.	Transplanting date	pH	Soil test ²				
			EC (dS·m ⁻¹)	P	K (mg·kg ⁻¹)	Ca	Mg
1	17 Oct. 1995	5.9	0.1	185	30	733	54
2	29 Feb. 1996	5.8	0.0	247	37	695	43

²pH and EC determined on a 2 water : 1 soil ratio procedure, while elements are from a Mehlich-1 extractant (Hanlon et al., 1994).

Plants in Expt. 3 were irrigated every second day by floating flats in nutrient solution containing P at 0, 15, 30, 60, or 90 mg·L⁻¹ in a factorial combination with N at 60 or 100 mg·L⁻¹. Phosphorus was supplied from Na₂HPO₄, while N was supplied from NH₄NO₃. Other nutrients were supplied as described above. Expt. 3 was conducted during the winter, average daily maximum and minimum media temperatures were 29 and 21 °C, respectively.

Expts. 1 and 2 were arranged in a randomized complete-block experimental design with five treatments, each replicated four times. In Expt. 3 a randomized complete-block experimental design was used with 10 treatments arranged in a factorial combination of five levels of P and two levels of N, each replicated four times.

Plants, five from each treatment, were sampled at 28 d after sowing (DAS) for growth measurements. Measurements included shoot and root fresh and dry weight, and leaf area (measured by a LI-3100 leaf area meter; LI-COR, Lincoln, Neb.). Growth variables calculated were: root to shoot ratio (RSR = dry root weight ÷ dry shoot weight), relative growth rate (RGR = [ln (final total dry weight) – ln (initial total dry weight) ÷ (final time – initial time)]), net assimilation rate (NAR = [final total dry weight – initial total dry weight] ÷ (final time – initial time) × {(ln (final leaf area) – ln (initial leaf area)) ÷ (final leaf area – initial leaf area)}), specific leaf area (SLA = leaf area ÷ dry shoot weight), leaf area ratio (LAR = leaf area ÷ total dry weight), and root weight ratio (RMR = dry root weight ÷ total dry weight) (Dubik et al., 1992; Hunt, 1978, 1982).

At the final sampling date in Expts. 2 and 3, fresh roots were scanned with a desktop scanner (Hewlett Packard, Greenley, Colo.) and analyzed with MacRHIZO software (Regent Instruments, Quebec) at 300 dpi for length, area, and diameter. Additionally, pull force, the force required to pull a lettuce transplant from the flat, was measured using a model DPP Dial Push-Pull Gauge (John Chatillon and Sons, Kew Gardens, N.Y.) attached to a binder clip. Pulling success (%) was calculated from five plants sampled within each replicate that could be removed from the flats without breakage. Planting dates for all experiments are listed in Table 1.

Plant tissue was dried, ground, and digested in H₂SO₄ and H₂O₂, and the samples were sent to the Analytical Research Laboratory, Univ. of Florida, and analyzed for P with a model 61-E Inductively Coupled Plasma Spectrometer (Thermo Jarell Ash Corp., Franklin, Mass.). Nitrogen was determined on a 300 Series Rapid Flow Analyzer (ALPKEM Corp., Wilsonville, Ore.).

Data were subjected to analysis of variance using the Statistical Analysis System (SAS Institute, Cary, N.C.). Treatment sums of squares were partitioned into linear and quadratic polynomial contrasts.

Field experiments. Plants from Expts. 2 and 3 were transplanted into an Arredondo fine sandy soil (loamy, siliceous, hyperthermic Grosarenic Paleudults) in beds covered with white-on-black polyethylene-mulch (0.038 mm thick) at the Univ. of Florida Horticultural Research Unit, Gainesville, Fla. (Table 1). Expt. 2 was a randomized complete-block experimental design with five greenhouse P treatments replicated four times. Expt. 3 was a randomized complete-block experimental design, with 10 greenhouse fertilization treatments in a factorial arrangement of five levels of P and two levels of N, each replicated four times.

Preplant fertilizer (13N-0P-10.8K) was applied broadcast and incorporated in the field bed at 230 kg·ha⁻¹. Raised beds, spaced 1.2 m center to center, were fumigated with methyl bromide and then covered with the polyethylene mulch. Seedlings were transplanted (30 plants per plot) on double offset rows with a spacing of 0.3 m between plants and between rows on the bed (equivalent to 54,000 plants per ha).

Just after transplanting, 100 mL of nutrient solution (150 mg·L⁻¹ N from 20N-8.6P-16.7K)

was applied to each transplant. Irrigation water was applied twice daily for 20 min each cycle, using drip irrigation lines placed on the center of the bed with emitters spaced 0.3 m apart. Tensiometers (Irrometer Co., Riverside, Calif.) were used to monitor soil moisture adequacy in the root zone. The root zone area was maintained at about –10 kPa according to Hochmuth and Smajstrla (1997). Starting 1 week after transplanting, fertilizer (15 kg·ha⁻¹ N and 16 kg·ha⁻¹ K, supplied from NH₄NO₃ and KNO₃), was injected once weekly using a venturi pump (Netafim Irrigation, Altamonte Springs, Fla.), with the last application made 1 week before harvest, to provide a total of 150 kg·ha⁻¹ N and 180 kg·ha⁻¹ K. Cultural management practices were similar to those used commercially in Florida (Maynard et al., 1999).

The plants were harvested 64 d after transplanting, December (Fall), and May (Spring). At head maturity, the center 20 plants in a plot were cut, weighed individually, and then 10 heads were assessed for firmness and cut longitudinally for height, diameter, stem width, and core length measurements. Wrapper leaves were sampled at harvest and analyzed for total P and Kjeldahl N as previously described for greenhouse experiments. Field data were subjected to analysis of variance using the Statistical Analysis System (SAS Institute, Cary, N.C.). Treatment sums of squares were partitioned into linear and quadratic polynomial contrasts.

Results

Expts. 1 and 2. Fresh and dry shoot weight increased quadratically in response to applied P for plants 29 and 28 DAS (Tables 2 and 3). The highest increases in shoot weight in response to applied P occurred between 0 and 15 mg·L⁻¹, regardless of sampling date. For plants sampled 28 DAS, fresh and dry root weight increased linearly, with increasing P applied. For plants grown for 28 d, root length and area increased linearly in response to applied P, but root diameter was unaffected (Table 3). Leaf area increased quadratically with applied P, regardless of sampling date. Phosphorus fertilization did not affect pull force, but improved pulling success from 30% to ≈90%. Most of the growth response to P occurred between 0 and 15 mg·L⁻¹ P (Table 3).

At 28 DAS with P applied, leaf tissue P increased quadratically from about 1 to 6 g·kg⁻¹ (Table 4). Root:shoot ratios decreased in quadratic fashion in response to applied P,

Table 2. Root and shoot characteristics of lettuce transplants as affected by P nutrition 29 d after sowing (Expt. 1, June/July).

Phosphorus applied (mg·L ⁻¹)	Fresh shoot	Wt (mg)			Leaf area (cm ²)	Leaf tissue P (g·kg ⁻¹)	Root : shoot ratio
		Dry shoot	Fresh root	Dry root			
0	685	58.0	304	25.3	25.0	1.2	0.44
15	1268	85.4	307	23.8	46.8	3.0	0.29
30	1297	85.6	301	23.8	48.1	4.2	0.28
45	1401	92.3	320	24.7	50.3	4.6	0.27
60	1297	89.8	341	26.6	48.5	4.6	0.30
Response	Q**	Q**	NS	NS	Q**	Q**	Q**

NS, **Linear (L) or quadratic (Q) effects nonsignificant (NS) or significant at $P \leq 0.05$ or 0.01.

Table 3. Root and shoot characteristics of lettuce transplants as affected by P nutrition 28 d after sowing (Expt. 2, September/October).

Phosphorus applied (mg·L ⁻¹)	Wt (mg)				Root length (cm)	Root area (cm ²)	Root diam (mm)	Leaf area (cm ²)	Pull force (N) ²	Pulling success (%)
	Fresh shoot	Dry shoot	Fresh root	Dry root						
0	762	58.9	245	19.1	246	24.4	0.32	25.2	0.019	30
15	2080	113.9	293	21.0	271	27.9	0.33	66.3	0.021	95
30	2076	111.7	298	20.8	275	27.3	0.32	66.4	0.019	90
45	2067	116.9	329	22.8	305	30.6	0.32	65.5	0.019	85
60	2115	117.9	344	23.7	310	31.5	0.32	67.1	0.020	90
Response	Q**	Q**	L**	L*	L**	L**	NS	Q**	NS	Q*

NS, *, **Linear (L) or quadratic (Q) effects nonsignificant (NS) or significant at $P \leq 0.05$ or 0.01.

²N = Newtons.

regardless of sampling date. The largest RSR values were obtained with 0 P. Root : shoot ratios were similar for all P treatments within sampling dates.

In Expt. 2, RGR was not affected by P and NAR decreased quadratically to applied P. Net assimilation rate was greatest with 0 P, but the total production of dry matter during the same period was greater when any level of P was applied.

Both SLA and LAR increased quadratically with applied P. Lowest SLA and LAR values were obtained with 0 P, while there were similar values with any level of P. The reduction in SLA and LAR values for plants grown with 0 P reflects the reduction in both leaf size and assimilate production (Dubik et al., 1990).

LMR values increased quadratically while RMR values decreased quadratically in response to applied P. For plants grown for 28 DAS without P, ≈75% of the dry matter was allocated to shoots and 25% to roots. Plants grown with 15 to 60 mg·L⁻¹ P allocated about 84% of dry matter to shoots, with only 16% to roots. Once again, added P increased dry matter accumulation more in the shoots than in the roots.

Expt. 3 Winter, Greenhouse. At all added P levels (15 to 60 mg·L⁻¹ P), high-quality transplants were produced. Transplants grown with 0 P were inferior to those plants grown with any other level of P since subsequent pulling was difficult (data not shown). In Expt. 3, N was included as a variable to compare a commercial standard (100 mg·L⁻¹ N) with a lower level (60 mg·L⁻¹ N) at selected levels of P. Since, in Expts. 1 and 2, root weight may not have been maximized at 60 mg·L⁻¹, a 90 mg·L⁻¹ P treatment was included. For plants sampled 28 DAS, dry shoot weight increased quadratically with applied P at both levels of N (Table 5). The response to P was greater with 100 than with 60 mg·L⁻¹ N.

Nitrogen did not interact with P to influence dry root weight (Table 5). Dry root weight increased quadratically in response to applied P at 28 DAS. The major increases in response to P occurred between 0 and 15 mg·L⁻¹. Root weight accumulation was adversely affected by increased N at both sampling dates. Root length, area, and diameter increased quadratically in response to applied P. Applied N did not influence root length, area, or diameter. Leaf area response to applied P was quadratic, regardless of N applied. The response of leaf area to P was greater with 100 than with 60 mg·L⁻¹ N.

There were no P × N interactions for leaf tissue N at 28 DAS (Table 6), but N concen-

Table 4. Influence of P nutrition on growth characteristics of lettuce transplants 28 d after sowing (Expt. 2, September/October).

Phosphorus applied (mg·L ⁻¹)	Leaf tissue P (g·kg ⁻¹)	Root : shoot ratio	Relative growth rate (mg·mg ⁻¹ ·wk ⁻¹)	Net assimilation rate (mg·cm ⁻² ·wk ⁻¹)	Specific leaf area (cm ² ·mg ⁻¹)	Leaf area ratio	Leaf wt ratio	Root wt ratio
0	1.2	0.33	0.67	1.92	0.43	0.32	0.75	0.25
15	3.5	0.18	0.60	1.14	0.58	0.49	0.85	0.15
30	5.5	0.19	0.60	1.11	0.60	0.50	0.84	0.16
45	5.8	0.19	0.60	1.17	0.56	0.47	0.84	0.16
60	6.2	0.20	0.60	1.18	0.57	0.48	0.83	0.17
Response	Q**	Q**	NS	Q**	Q**	Q**	Q**	Q**

NS, *, **Linear (L) or quadratic (Q) effects nonsignificant (NS) or significant at $P \leq 0.01$.

Table 5. Root and shoot characteristics of lettuce transplants as affected by P and N nutrition 28 d after sowing (Expt. 3, February).

Nutrient applied (mg·L ⁻¹)	Dry shoot wt (mg)		Dry root wt (mg)	Root length (cm)	Root area (cm ²)	Root diameter (mm)	Leaf area (cm ²)	
	N ₁ ²	N ₂					N ₁ ²	N ₂
P								
0	12.7	12.1	8.6	94	8.4	0.28	4.2	4.2
15	82.1	104.7	24.5	282	26.7	0.30	48.4	68.1
30	83.5	105.6	23.9	276	26.0	0.30	50.3	70.6
60	82.8	104.4	24.4	306	29.5	0.31	55.0	69.9
90	81.0	101.6	25.4	292	27.0	0.29	49.0	70.6
Response	Q**	Q**	Q**	Q**	Q**	Q**	Q**	Q**
N								
60			23.2	255	24.2	0.30		
100			19.5	245	22.9	0.30		
Response			**	NS	NS	NS		
P × N	**		NS	NS	NS	NS	**	

²N₁ = 60 mg·L⁻¹; N₂ = 100 mg·L⁻¹.

NS, **Nonsignificant (NS) or significant at 1% levels.

trations decreased quadratically in response to applied P. The response was probably a dilution effect since transplants were larger at any level of P as compared with 0 P. Plants grown with 100 mg·L⁻¹ N had more N in the leaves than did those grown with 60 mg·L⁻¹ N. Leaf tissue P increased quadratically with applied P. The response of leaf tissue P to applied P was greater with 100 than with 60 mg·L⁻¹ N.

There were no P by N interactions for RSR for plants sampled 28 DAS. Root : shoot ratios decreased quadratically in response to applied P. The largest RSR values were obtained with 0 P. Plants grown with 60 mg·L⁻¹ N had larger RSR values than those grown with 100 mg·L⁻¹. RGR values had increased quadratically in response to applied P (Table 6). There were no P × N interactions for RGR and NAR for plants grown to 28 DAS, and N did not influence RGR values (Table 6). Neither P nor N influenced NAR values at 28 DAS.

SLA values increased quadratically in response to applied P, most of the response occurring between 0 and 15 mg·L⁻¹ (Table 7).

There were no P × N interactions for SLA. Nitrogen had no influence on LAR except through its interaction with P. The response of LAR to P was greater with 100 than with 60 mg·L⁻¹ N. LAR increased with all levels of applied P.

LMR values increased quadratically for plants sampled 28 DAS, while RMR values decreased quadratically in response to applied P. Nitrogen had no influence on LMR or RMR, but LMR was increased, while RMR was decreased with all levels of applied P.

Field experiment, Fall. Lettuce head weight increased quadratically in response to the floatation P fertilization of the transplants from Experiment 2 (Table 8). Firmness, head height, stem width, and core length increased quadratically with P supplied in the transplant culture cycle. Firmness and head height ratings were improved by P supplied in the greenhouse culture cycle, while stem width and core length were enlarged. Heads were less developed with 0 P, while heads from transplants produced with 15 to 60 mg·L⁻¹ P were more developed, indicating greater earliness. At

harvest, tissue P concentrations were similar, regardless of P supplied in the greenhouse culture cycle as should be expected for plants subsequently grown in a field with soil high in available P.

Field experiment, Spring. Phosphorus $\times$ N interactions were nonsignificant for head mass or head quality characteristics (Exp. 3, Table 8). There was a positive linear response of

head weight to greenhouse cycle transplant P. Head weight was improved at harvest with all transplant P fertilization treatments, but was unaffected by transplant N fertilization (data not shown). Stem width increased quadratically, while core length increased linearly in response to transplant P treatment. Stem width and core length were enlarged by increasing transplant P, indicating greater earliness, but

were unaffected by transplant N fertilization. Lettuce head firmness, height, and diameter were unaffected by transplant P or N. At harvest, tissue N and P concentrations were similar regardless of transplant P or N fertilization.

Discussion

Fertigation occurred every second day in Expt. 3 vs. every 2 to 4 d in Expt. 2. When fertigation was applied every 2 d, fresh and dry root mass increased in response to $15 \text{ mg}\cdot\text{L}^{-1}$ P, with no further increases as P concentrations increased to $90 \text{ mg}\cdot\text{L}^{-1}$, even though the initial P concentration in the medium was low ($0.4 \text{ mg}\cdot\text{kg}^{-1}$). In Expt. 2, root weight increased with each level of P applied probably because the initial P concentration in the media was low ($0.6 \text{ mg}\cdot\text{kg}^{-1}$) (Table 1). Compared to Expt. 1, where the media P concentration was ($12.4 \text{ mg}\cdot\text{kg}^{-1}$), perhaps even $60 \text{ mg}\cdot\text{L}^{-1}$ P was not optimal with the irrigation programs used. Therefore, in a medium with $<0.5 \text{ mg}\cdot\text{kg}^{-1}$ water-extractable P, frequent fertigation is desirable.

These experiments suggested that P applied via the floatation irrigation system improved growth of both roots and shoots of lettuce transplants, especially when medium P was low. Melton and Dufault (1991) reported that 5 to $45 \text{ mg}\cdot\text{L}^{-1}$ P did not influence tomato transplant shoot and root growth, and Tremblay et al. (1987) reported that increasing P from 100 to $200 \text{ mg}\cdot\text{L}^{-1}$ did not influence root growth of celery transplants. However, a 0 P treatment was not included in their studies. Lorenz and Vittum (1980) reported that the critical tissue P concentration for most vegetable species is $\approx 3.0 \text{ g}\cdot\text{kg}^{-1}$ of dry weight. This is equivalent to an application of $15 \text{ mg}\cdot\text{L}^{-1}$ P in the present study. In all three experiments, tissue P in plants receiving no P was $\approx 1.0 \text{ g}\cdot\text{kg}^{-1}$, while it ranged from 3.0 to $8.6 \text{ g}\cdot\text{kg}^{-1}$ in shoots receiving P. Based on these results, a range of 3.0 to $4.0 \text{ g}\cdot\text{kg}^{-1}$ P is consistent with adequate tissue P concentration for production of high quality lettuce transplants. However, why increased N increased P concentrations is not clear.

Table 6. Influence of P and N nutrition on tissue N and P and growth characteristics of lettuce transplants 28 d after sowing (Expt. 3, February).

Nutrient applied ($\text{mg}\cdot\text{L}^{-1}$)	Leaf tissue N ($\text{g}\cdot\text{kg}^{-1}$)	Leaf tissue P ($\text{g}\cdot\text{kg}^{-1}$)		Root : shoot ratio	Relative growth rate ($\text{mg}\cdot\text{mg}^{-1}/\text{wk}$)	Net assimilation rate ($\text{mg}\cdot\text{cm}^{-2}/\text{wk}$)
		N_1^z	N_2			
P						
0	48.5	0.9	1.0	0.70	0.25	1.23
15	24.6	3.8	4.0	0.27	0.73	1.46
30	23.5	4.8	5.9	0.26	0.66	1.30
60	22.7	5.1	7.4	0.27	0.64	1.21
90	22.1	5.8	8.6	0.29	0.63	1.23
Response	Q**	Q**	Q**	Q**	Q**	NS
N						
60	24.7			0.40	0.56	1.33
100	31.8			0.31	0.61	1.25
Response	**			**	NS	NS
P $\times$ N	NS	**		NS	NS	NS

$^z\text{N}_1 = 60 \text{ mg}\cdot\text{L}^{-1}$; $\text{N}_2 = 100 \text{ mg}\cdot\text{L}^{-1}$. Quadratic (Q).

NS, **Nonsignificant or significant at 1% levels, respectively.

Table 7. Influence of P and N nutrition on growth characteristics of lettuce transplants 28 d after sowing (Expt. 3, February).

Nutrient applied ($\text{mg}\cdot\text{L}^{-1}$)	Specific leaf area ($\text{cm}^2\cdot\text{mg}^{-1}$)	Leaf area ratio ($\text{cm}^2\cdot\text{mg}^{-1}$)		Leaf weight ratio		Root weight ratio	
		N_1^z	N_2	N_1	N_2	N_1	N_2
P							
0	0.34	0.19	0.21	0.58	0.60	0.42	0.40
15	0.62	0.45	0.53	0.76	0.82	0.24	0.18
30	0.63	0.46	0.55	0.76	0.83	0.24	0.17
60	0.67	0.50	0.55	0.76	0.83	0.24	0.17
90	0.65	0.45	0.57	0.74	0.82	0.26	0.18
Response	Q**y	Q**	Q**	Q**	Q**	Q**	Q**
N							
60	0.56						
100	0.61						
Response	**						
P $\times$ N	NS	*		**		**	

$^z\text{N}_1 = 60 \text{ mg}\cdot\text{L}^{-1}$; $\text{N}_2 = 100 \text{ mg}\cdot\text{L}^{-1}$.

y Quadratic (Q).

NS, *, **Nonsignificant or significant at 5% or 1% levels, respectively.

Table 8. Effects of P nutrition during transplant production on lettuce head mass and head quality characteristics.

Phosphorus applied (mg·L ⁻¹)	Head				Stem width (mm)	Core length (mm)	Leaf tissue N (g·kg ⁻¹)	Leaf tissue P (g·kg ⁻¹)
	Wt (g)	Firmness rating ^z (1–5)	Height (mm)	Diam (mm)				
Expt. 2, harvested 20 Dec.								
0	601	4.3	112	120	25	38		2.9
15	743	4.8	124	122	30	54		3.1
30	711	4.9	123	124	31	58		3.0
45	721	4.9	130	129	30	57		2.8
60	738	4.8	127	121	31	63		2.7
Response	Q*	Q**	Q*	NS	Q**	Q*		NS
Expt. 3, harvested 2 May								
P								
0	451	4.6	124	103	22	34	36.6	2.1
15	533	4.9	124	107	24	36	35.0	2.0
30	517	4.8	124	104	24	36	34.9	2.1
60	524	4.8	123	108	24	38	36.8	2.1
90	552	4.8	124	108	24	38	34.3	2.2
Response	L**	NS	NS	NS	Q*	L*	NS	NS

^zLettuce head firmness on a scale of 1 = loose, 5 = compact.

NS, *, **Linear (L) or quadratic (Q) effects nonsignificant (ns) or significant at $P \leq 0.05$ or 0.01.

Regardless of season, average daily maximum and minimum temperature of the medium was similar, i.e., 31, 33 and 29 °C, and 22, 26 and 21 °C, respectively, for Expts. 1, 2, and 3, respectively. Improved shoot growth in Expt. 2 (September/October) than in Expt. 3 (February) was probably associated with higher temperatures inside the greenhouse during the fall. In Expt. 3, transplants produced with 0 P were smaller than those in previous experiments, probably because P was low (0.4 mg·kg⁻¹) in the peat+vermiculite mix, and frequent fertigations, without P, that may have diluted or leached any available P in the medium. Transplants produced with 0 P in Expt. 3 also grew poorly, regardless of N concentration. Shoot and root growth were similar at all levels of applied P. Nitrogen at 100 mg·L⁻¹ improved shoot growth, especially in combination with P, but reduced root growth in comparison with N at 60 mg·L⁻¹.

In general, RGR increased while NAR decreased when P was applied. Both RGR and NAR were higher at 21 (data not shown) than at 28 DAS, indicating that younger plants were more efficient than older ones. With added P, RSR was lower in Expt. 2 than in Expt. 3; higher temperatures during Expt. 2 stimulated shoot growth at the expense of root growth. Weston and Zandstra (1989) reported that P from 15 to 60 mg·L⁻¹ had no effect on RSR values of tomato transplants. In all the experiments, LMR and RMR were similar, suggesting dry matter allocation between shoots and roots did not change over time.

The response of root length and area paralleled that of root weight to applied P, regardless of time of transplant production. High-quality transplants had total root lengths between 280 and 300 cm, and total root area between 26 and 30 cm². All levels of applied P improved pulling success, but pull force was unaffected.

In the field, lettuce head weight was increased by transplant P fertilization, regardless of time of production or level applied. Leaf tissue P concentrations at harvest were

not affected by P treatment at harvest. Hochmuth et al. (1991) reported that values of 25 to 50 g·kg⁻¹ P were indicative of an adequate P range for wrapper leaves of crisphead lettuce. Values of tissue P were slightly less than this in Expt. 3, but plants appeared to be healthy with tissue P of 21 g·kg⁻¹. Stem width and core length were improved by transplant P, indicating that P fertilization hastened maturity, resulting in larger plant size.

Therefore, for lettuce transplants grown with floatation irrigation, maintaining P levels in the medium so that tissue concentrations are in the range of 35 to 50 g·kg⁻¹ P is essential to optimize plant size, overall growth, especially root growth, and ultimately crop yield. Regardless of season, this tissue sufficiency range can be accomplished with as low as 15 to 30 mg·L⁻¹ P in the irrigation water every 2 to 3 d, regardless of medium P content.

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