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 graveolens 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 producing 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.
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 = [ln (final total dry weight) – ln (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 (Régent Instruments, Quebec) at 300 dpi for length, and 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.

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 | EC (ds m⁻¹) | NO₃-N | P (mg kg⁻¹) | 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 |

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 | Dry shoot | Fresh root | Dry root | Leaf area (cm²) | Leaf tissue P (g kg⁻¹) | Root : shoot ratio |
|----------------------------|-------------|-----------|------------|----------|----------------|------------------------|-------------------|
| 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 ≤ 0.05 or 0.01.*
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, about 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 concentrations 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 × N interactions for SLA for plants sampled 28 DAS. Root : shoot ratios decreased quadratically in response to applied P. The largest SLA values were obtained with 0 P. Plants grown with 60 mg·L⁻¹ N had larger SLA values than those grown with 100 mg·L⁻¹ P. 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 floating 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
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 (mg·L⁻¹) | Leaf tissue N (g·kg⁻¹) | Leaf tissue P (g·kg⁻¹) | Relative growth rate (mg·mg⁻¹/wk) | Net assimilation rate (mg·cm⁻²/wk) |
|--------------------------|------------------------|------------------------|-----------------------------------|-----------------------------------|
| P                        | N                      | N                      | G                                 | N                                 |
| 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                       | 23.3 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                                |
| NS                       | NS                     | NS                     | NS                                | NS                                | NS                                |

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

| Nutrient applied (mg·L⁻¹) | Specific leaf area (cm²·g⁻¹) | Leaf area ratio (cm²·g⁻¹) | Leaf weight ratio (g·kg⁻¹) | Root weight ratio (g·kg⁻¹) | P × N |
|--------------------------|-------------------------------|---------------------------|----------------------------|-----------------------------|-------|
| P                        | N                             | N                         | N                          | N                          | NS    |
| 0                        | 0.34                          | 0.19                      | 0.21                       | 0.58                        | 0.60  |
| 15                       | 0.62                          | 0.45                      | 0.53                       | 0.76                        | 0.82  |
| 30                       | 0.63                          | 0.46                      | 0.55                       | 0.76                        | 0.83  |
| 60                       | 0.67                          | 0.50                      | 0.55                       | 0.76                        | 0.83  |
| 90                       | 0.65                          | 0.45                      | 0.57                       | 0.74                        | 0.82  |
| Response Q               | Q                             | Q                         | Q                          | Q                           | NS    |

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

| Phosphorus applied (mg·L⁻¹) | Wt (g) | Firmness rating (1–5) | Height (mm) | Diam (mm) | Stem width (mm) | Core length (mm) | Leaf tissue N (g·kg⁻¹) | Leaf tissue P (g·kg⁻¹) |
|-----------------------------|--------|-----------------------|-------------|-----------|----------------|-------------------|-------------------------|------------------------|
| 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 L                 | L      | NS                    | NS          | NS        | Q              | L                | NS                      | NS                     |

Expt. 3, harvested 2 Field experiment, Spring. Phosphorus nutrition influenced lettuce growth characteristics (Exp. 3, Table 8). There was a positive linear response of harvested tissue 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 2d, fresh and dry root mass increased in response to 15 mg·L⁻¹ P, with no further increases as P concentrations increased to 90 mg·L⁻¹, even though the initial P concentration in the medium was low (0.4 mg·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 mg·kg⁻¹) (Table 1). Compared to Expt. 1, where the media P concentration was (12.4 mg·kg⁻¹), perhaps even 60 mg·L⁻¹ P was not optimal with the irrigation programs used. Therefore, in a medium with <0.5 mg·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 mg·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 mg·L⁻¹ did not influence growth of celery transplants. However, a P treatment was not included in their studies. Lorenz and Vittum (1980) reported that the critical tissue P concentration for most vegetable species is 3.0 g·kg⁻¹ of dry weight. This is equivalent to an application of 15 mg·L⁻¹ P in the present study. In all three experiments, tissue P in plants receiving no P was 1.0 g·kg⁻¹, while it ranged from 3.0 to 8.6 g·kg⁻¹ in shoots receiving P. Based on these results, a range of 3.0 to 4.0 g·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.
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, 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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