Effects of Tissue Phosphorus and Nitrogen in *Impatiens wallerana* on Western Flower Thrips (*Frankliniella occidentalis*) Population Levels and Plant Damage

Yan Chen¹ and Kimberly A. Williams²

Department of Horticulture, Forestry, and Recreation Resources, Kansas State University, Manhattan KS 66506-5506

Brent K. Harbaugh³ and Michelle L. Bell⁴

Gulf Coast Research and Education Center, University of Florida, Bradenton, FL 34207

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Abstract. Host-plant nutritional status may affect the incidence and development of western flower thrips (WFT; *Frankliniella occidentalis* Pergande). Two greenhouse experiments were conducted to determine the responses of WFT population levels on impatiens (*Impatiens wallerana* Hook.f.) when plants were fertilized with commercially practiced rates of nitrogen (N) and phosphorus (P). Impatiens ‘Dazzler Violet’ were grown with nutrient treatment combinations of 2 N rates (8 and 20 mM) by 2 P rates (0.32 and 1.28 mM). Individual plants grown in thrips-proof cages were inoculated with WFT at 2 or 4 weeks after transplant, in separate experiments, representing vegetative or reproductive stages of plant growth, respectively. Plants were destructively sampled weekly for 4 weeks following inoculation. Plant tissue N and P concentrations were significantly different across treatments: 8 and 20 mM N resulted in 4.9% and 6.3% N in tissue, respectively; 0.32 and 1.28 mM P resulted in 0.37% and 0.77% P in tissue, respectively. Nitrogen rates had no effect on WFT population levels. However, 4 weeks after inoculation with adult female WFT during the vegetative growth stage, plants fertilized with 1.28 mM P had more adult WFT than those fertilized with 0.32 mM P. Feeding damage varied depending on whether plants were inoculated in the vegetative stage with adult WFT or during reproductive growth with immature WFT. Plant size and number of flowers were lower in plants inoculated during the vegetative growth stage with adult WFT but were not affected when inoculation with immature WFT occurred during the reproductive stage, as most WFT were found feeding inside the nectariferous spurs of the flowers. Tissue N was lower in WFT-inoculated plants compared to noninoculated plants in both experiments.

Western flower thrips (*Frankliniella occidentalis* Pergande; WFT) is an insect pest of many field and greenhouse crops (Oetting et al., 1993; Robb, 1989). They use the maxillary stylets of their mouth cone to rasp or suck plant sap, resulting in the collapse of surrounding cells (Lewis, 1973; Chrisholm and Lewis, 1984;

Hunter and Ullman, 1989). Visual damage includes feeding lesions, leaf distortion and petal discoloration, all of which reduce the aesthetic quality and marketability of ornamental plants. More importantly, WFT vectors impatiens necrotic spot virus (INSV) and several strains of tomato spotted wilt virus (TSWV) (Allen and Broadbent, 1986; Ullman et al., 1998).

The use of insecticides as an exclusive control tactic for WFT is problematic because it is difficult to target thrips inside flowers and in the root medium. In addition, sole use of insecticides contributes to problems of pest resurgence and development of insecticide resistance (Immaraju et al., 1992; Lewis, 1997). Several biological control agents have been used against WFT with varying degrees of effectiveness (Thompson et al., 2002). However, commercial producers generally have very low tolerance for WFT because this pest vectors viruses, and because any aesthetic damage diminishes the value of ornamental crops. An integrated pest management (IPM) program that incorporates all available cultural, biological and chemical control measures is required for the management of WFT. A cultural control

that may augment other control strategies is nutrition management.

Nutrition management is necessary for timely and profitable crop production, but at the same time, it changes plant nutrient content, morphology, and plant defense mechanisms against pests (Norris and Kogan, 1980; Suresh, 1988). Because manipulation of fertilizer is relatively easy in greenhouse production and compatible with biological control, it may increase the economic feasibility of biological control by reducing the potential for pest population increase. Previous studies suggest that, in general, phytophagous insect pests prefer plant tissue with increased nitrogen and protein and low carbohydrate and phenol content (Ananthakrishnan, 1992; McNeil, 1978). However, little research has been done to evaluate thrips–host–plant nutrition response (Mollema and Cole, 1996; Schuch et al., 1998), and no research has evaluated the role of P in this response.

Impatiens wallerana is an economically important spring bedding plant crop (NASS, 2001) and a major host plant of WFT. For this research, ‘Dazzler Violet’ was selected because of its uniform growth habit, dark petal coloration and lack of purple blotches on the abaxial surface of the foliage. Thrips damage on impatiens includes tan lesions on leaves, distortion of newly developed leaves and flowers, flower bud abortion, and discolored strips of cells on flower petals.

The objectives of this research were to 1) determine the effects of N × P fertilization regimes on tissue nutrient concentrations of impatiens and their sequential effect on WFT population levels, and 2) investigate the relationship between WFT population and feeding damage on impatiens during the vegetative and reproductive growth stages.

Materials and Methods

Two greenhouse experiments were conducted at Kansas State University in Manhattan. Experiment 1 was conducted from 15 Feb. to 1 June 2001, and Expt. 2 from 20 May to 24 Aug. 2001. *Impatiens wallerana* ‘Dazzler violet’ were propagated from seed in both experiments. A replacement cultivar, ‘Improved Dazzler Violet,’ was released in 2000 by Pan American Seed Co. (West Chicago, Ill.), but only ‘Dazzler Violet’ was used to maintain consistency with previous experiments (Williams, Bell, and Harbaugh, unpublished data).

Treatment structure was factorial with 2 N (8 and 20 mM) by 2 P (0.32 and 1.28 mM) by 2 WFT inoculation rates: 0 (no-WFT control) and 10 WFT per plant (WFT-inoculated) sampled over 4 weeks. Fertilizer rates were selected based on previous research and chosen because they resulted in high impatiens quality (based on plant size and aesthetic appearance) but variable tissue N and P concentrations (Jonas and Williams, unpublished data). Current fertilization recommendations for impatiens range from 7 to 18 mM N (Dole and Wilkins, 1999; Whipker et al., 1999). Therefore, nitrogen rates used in these experiments are within commercially practiced ranges.

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¹Graduate research assistant.

²Associate professor; to whom reprint requests should be directed.

³Professor.

⁴Currently manager of horticultural research, SePRO Corp., 11550 North Meridian St., Suite 600, Carmel, IN 46032-4565.

Experimental design was a randomized complete block (RCBD) with an unequal number of replications for the no-WFT control versus WFT-inoculated treatments. In Expt. 1, four replications of WFT-inoculated treatments and two replications of no-WFT control treatments were blocked across a temperature gradient resulting from the use of evaporative cooling pads in a glass greenhouse. Because a primary purpose of no-WFT control plants was to determine tissue nutrient status over 4 weeks of sampling, two replications was adequate. Each experimental unit consisted of four pots, and one was sampled weekly over a 4-week period following inoculation with WFT. Pots of WFT-inoculated plants were randomly placed along the fertigation tubes on each bench, and no-WFT control plants were arranged as subplots along side the WFT-inoculated plants to receive the corresponding fertilizer treatment. Combinations of WFT-inoculated and no-WFT control plants that received the same nutrition treatment were statistically analyzed as whole plots.

The design of Expt. 2 was similar to Expt. 1, except that the number of replications of WFT-inoculated treatments was increased to eight, and the number of pots in an experimental unit of no-WFT control treatments was two and sampled at only 2 and 4 weeks after inoculation.

In both experiments, four extra plants of each of the four nutrient treatment combinations were randomly placed throughout the experiment and sampled at the time of WFT inoculation to determine the starting point of their nutritional status. As a RCBD with an unequal number of blocks, PROC MIXED and LSMEANS was used for data analyses (SAS, Cary, N.C.). This statistical procedure compares the computed adjusted means, so it accounts for different variance at each sample date.

Impatiens seeds were sown directly into 48-cell packs (130 cm³ in volume) and grown in a 2.5 × 1.2 × 1.2-m tent covered with No-thrips Insect Screen (Green.Tek, Inc., Edgerton, Wis.) to avoid natural infestation with WFT. Root medium consisted of a ratio of 7 sphagnum peatmoss (Premier, Red Hill, Pa.): 3 perlite (Lite-Weight Products, Kansas City, Kans.) that was amended with the following weights (in kg·m⁻³): 6 dolomitic limestone, 0.9 gypsum, and 0.9 Micromax (Scott-Sierra Co., Marysville, Ohio). Fertilizer applications began when seedlings developed two pairs of true leaves, on 12 Mar. and 2 July in Expts. 1 and 2, respectively.

Plants were transplanted into 10-cm-round, green pots (480 cm³ in volume) when seedlings had four pairs of true leaves, on 1 Apr. and 16 July in Expt. 1 and 2, respectively. Pots were placed into individual cages that had been constructed from 19-L cardboard ice cream buckets (38 cm tall × 26 cm diameter round) with four 14 × 27-cm apertures cut into the sidewalls that were covered with No-Thrips Screen and sealed with silicone). About 460 μmol·s⁻¹·m⁻² supplemental irradiance from high-pressure sodium lamps (Sunlight Supply, Inc., Vancouver, Wash.) was provided from 1900 PM to 0000 HR, resulting in a 16-h photoperiod. Irradiance

inside the cage was ≈70% of the level outside the cage, which was adequate for impatiens growth. Greenhouse temperatures were set at 24 °C day and 18 °C night after transplant. HOBO (Onset Computer Corp., Bourne, Mass.) temperature sensors were used to record actual temperatures and relative humidity inside the cages every 30 min. Temperatures ranged from 14 to 37 °C, with an average daily temperature of 22 °C in Expt. 1; and 15 to 41 °C, with an average daily temperature of 26 °C in Expt. 2. Relative humidity ranged from 23 to 96% with average of 60% in Expt. 1; and 29 to 94% with an average of 66% in Expt. 2.

Plants were grown in individual cages for 4 or 2 weeks before inoculation in Expts. 1 and 2, respectively, and were fertigated by pumping (140 gal/h) fertilizer treatment solutions through spaghetti tubes to pots inside each sealed cage. Plants were fertigated when container capacity dropped by 30% due to water loss based on weights of representative plants that were grown using the same procedure, but cages for these plants were not sealed and they were weighed at least once a day to determine time of fertigation. Leaching fraction was maintained between 5% to 15%. This methodology resulted in plants receiving fertilizer solution about once every the other day to almost daily as they reached maturity. The volume of fertilizer solution applied at each fertigation was recorded so that total nutrients applied could be calculated.

Western flower thrips were obtained from a laboratory colony maintained on green beans in the Dept. of Entomology, Kansas State Univ. (KSU), that was derived from a stock colony maintained by Diane Ullman (Dept. of Entomology, University of California–Davis) determined to be free of INSV and TSWV. The KSU colony was maintained under laboratory light conditions with temperatures set at 24 °C and relative humidity of 37%. WFT of different life stages (first and second instar nymphs, pupae, and adult) were kept in separate containers. WFT inoculation in Expt. 1 was conducted 4 weeks after transplant on 1 May. Plants were in the reproductive growth stage with an average of 20 flowers per plant. Ten second-instar nymphs were transferred into a 2.5-mL vial from the nymph stage colony by using a mini-brush. The vial was later opened and placed in the foliage canopy of a caged plant. In Expt. 2, nonflowering plants were inoculated with 10 adult female WFT 2 weeks after transplant on 30 July. Before inoculating plants, the adult WFT colony was placed in a 6 °C refrigerator for 20 min to slow movement. Female adults, which are broader and darker than males, were selected and placed into a 2.5-mL vial that was later opened and placed in leaves of a caged plant.

Plant growth data collected at each sample date included plant height, canopy width (the average of two measurements taken at right angles to each other), flower and bud numbers. Subjective damage ratings were assigned to individual plants based on a scale of 1 to 5, where 1 = slightly observable leaf stippling, 2 = observable leaf distortion and tan lesion development, 3 = significant leaf distortion and

tan lesion development, 4 = severe leaf distortion and tan lesion development with flower bud abortion, and 5 = severe leaf damage and flower bud abortion with stunted growth. The number of damaged leaves was also counted in Expt. 2, and the relationship between number of damaged leaves and visual damage ratings was positively correlated ($n = 160$, $r^2 = 0.77$, $y = 0.2 + 0.06x$; data not shown). For control plants, ratings were determined on the same plant for weeks 1 and 2, and similarly on the same plant for weeks 3 and 4, before that plant was destructively harvested.

To count WFT, caged plants were placed in a 6 °C refrigerator for 20 min to slow insect movement before removing the plant from the cage for destructive harvest. Immature and adult WFT were counted separately. Shoots were placed in a 41 × 29 × 25 cm clear plastic box (Rubbermaid Home Products, Wooster, Ohio) and uniformly shaken; WFT in flowers and buds were individually counted by destructively peeling back petals; terminal meristems were individually rinsed in a 48% ethanol stream and WFT collected were counted. Yellow sticky cards were placed in the cage with the pot and counted 2 weeks later. Adults found on sticky cards were counted as immatures because that was their life stage at the time of plant sampling. Total WFT number was the sum of adults and immatures.

Tissue samples consisted of ≈10 g fresh weight of leaf blades of youngest, fully expanded leaves from midcanopy foliage. Tissue was washed in 0.2 N HCl and distilled water and dried at 70 °C for 48 h, then ground in a stainless-steel Wiley mill to a particle size of <1 mm. Nitrogen was determined by dry combustion using a carbon–nitrogen analyzer (CN-2000; LECO Corp., St. Joseph, Minn.). Some of the leaf samples were dry-ashed at 500 °C, dehydrated in 6 mol·L⁻¹ HCl, and dissolved in 0.5 mol·L⁻¹ HCl, and K, Ca, and Mg were then analyzed using an inductively-coupled argon plasma atomic emission spectrophotometer (ICP-AES; Fisons Instruments, Dearborn, Mich.). Phosphorus was determined by the molybdate–vanadate colorimetric method (Chapman and Pratt, 1961) using a UV–VIS spectrophotometer (Perkin-Elmer, Norwalk, Conn.).

Results

In both experiments, significantly different tissue N and P concentrations were established at the time of inoculation (Table 1). The N × P interaction was not significant in either experiment. In Expt. 1, tissue P was 0.29% and 0.62% in plants fertilized with 0.32 and 1.28 mm P, respectively; whereas in Expt. 2, tissue P was 0.48% and 0.88% for these two P rates, respectively (Table 1). Plants were at different growth stages at the time of inoculation, so it is not surprising that tissue P concentrations were lower in Expt. 1 (reproductive growth stage) compared to Expt. 2 (vegetative growth stage).

Inoculation during reproductive stage (Expt. 1). During the 4-week period after inoculation, the no-WFT control plants fertilized

with different N and P treatment combinations resulted in similar, commercially acceptable growth based on plant height, width, and number of flowers. Dry weight was slightly different between plants fertilized with 0.32 and 1.28 mM P (Table 2). The N × P interaction was not significant for growth responses and results were similar to previous single factor N and P experiments (Jonas and Williams, unpublished data).

Tissue concentrations of N and P in no-WFT control plants were significantly different: 8 and 20 mM N rates resulted in 4.8% and 6.3% tissue N (Table 2), which represents adequate (within the range of critical tissue concentrations that results in maximum growth) and luxurious (exceeding the range of critical tissue concentrations without decreasing growth), respectively (e.g., Jacques et al., 1992; Mills and Jones, 1996; Jonas and Williams, unpublished data). The 0.32 and 1.28 mM P rates resulted in 0.29% and 0.66% tissue P, which represents adequate tissue P concentrations (e.g., van Iersel et al., 1998; Jonas and Williams, unpublished data). Therefore, different tissue N and P were established throughout the experiment that provided a variable diet for WFT across treatments.

The total number of WFT generally increased over the 4-week period after inoculation. Neither N nor P treatments had a significant effect on WFT populations when the data were analyzed over 4 weeks (for N: $F = 0.01$, $df = 64$, $p = 0.9647$; for P: $F = 0.48$, $df = 64$, $p = 0.4930$, $\alpha = 0.1$). However, during week three, higher WFT numbers were found on high P compared to low P plants ($F = 4.08$, $df = 16$, $p = 0.0143$, $\alpha = 0.1$, Table 3).

In this experiment, inoculation with immature WFT occurred when plants were in the reproductive stage. An average of 20 flowers were fully open per plant when inoculation occurred. Feeding damage from WFT was not significant compared to the no-WFT control plants until three weeks after inoculation ($F = 4.8$, $df = 16$, $p = 0.0436$, $\alpha = 0.05$). At week 4, the average damage rating of all WFT-inoculated plants was only 0.6 (Fig. 1).

When comparing WFT-inoculated versus no-WFT control plants at the end of the experiment, plants were similar in height, width, and dry weight (Table 4). Tissue N in inoculated plants was lower than in control plants, suggesting that WFT feeding reduced N uptake and utilization. However, tissue concentrations of P, K, Ca, and Mg were not affected by WFT feeding (Table 4).

Inoculation during vegetative stage (Expt. 2). The no-WFT control plants fertilized with different N and P treatment combinations resulted in similar, commercially acceptable growth based on all measured characteristics (Table 5). Tissue N concentration was significantly different between the 8 and 20 mM N treatments, resulting in 4.9% and 6.3% tissue N, respectively (Table 5). The N × P interaction was significant for tissue N: 8 mM N resulted in a lower N% at the high P level (1.28 mM) than at the low P level (0.32 mM), while the opposite was true for the 20 mM N treatments; however, the N main effect was not affected. These tissue

Table 1. Plant tissue N and P concentrations in plants fertilized with 2 N × 2 P treatments. Samples were collected at the time of inoculation on 2 May (Expt. 1) and 30 July 2001 (Expt. 2).

Treatment	Expt. 1		Expt. 2	
	N (%)	P (%)	N (%)	P (%)
<i>p</i> value ^z				
N	0.0173	0.1788	<0.0001	0.2339
P	0.9423	0.0013	0.0136	0.0277
N				
8 mM	5.0	0.49	4.8	0.76
20 mM	6.3	0.42	6.2	0.60
LSD _{0.05} ^y	0.9	NS	0.1	NS
P				
0.32 mM	5.7	0.29	5.6	0.48
1.28 mM	5.7	0.62	5.4	0.88
LSD _{0.05}	NS	0.12	0.1	0.32

^zN × P interaction was not significant in either experiment.

^yLeast significant difference for comparing two N or P rates at $\alpha = 0.05$, $n = 4$.

Table 2. Growth responses and tissue N and P concentrations in no-WFT control plants averaged over four sample dates (1 to 4 weeks after inoculation) during the reproductive growth stage (Expt. 1).

Treatment	Ht (cm)	Width (cm)	Dry wt (g)	No. of flower buds	N (%)	P (%)
<i>p</i> value ^z						
N	0.8819	0.3743	0.4441	0.8987	0.0001	0.3322
P	0.2482	0.4310	0.0229	0.1049	0.3838	0.0001
N						
8 mM	11.0	29.0	2.9	29.4	4.8	0.46
20 mM	11.2	23.3	3.1	29.0	6.3	0.48
LSD _{0.05} ^y	NS	NS	NS	NS	0.4	NS
P						
0.32 mM	10.7	29.6	2.7	26.3	5.6	0.29
1.28 mM	11.6	23.7	3.2	31.1	5.5	0.66
LSD _{0.05}	NS	NS	0.2	NS	NS	0.11

^zN × P interaction was not significant except for dry weight ($p = 0.0242$).

^yLeast significant difference for comparing two N or P rates at $\alpha = 0.05$, $n = 16$.

Table 3. Total number of WFT on inoculated plants at four sample dates after inoculation during the reproductive growth stage (Expt. 1) for P fertilizer treatments.

Treatment	Total WFT / plant			
	Week 1	Week 2	Week 3	Week 4
<i>p</i> value				
N	0.7763	0.5409	0.5999	0.2136
P	0.2500	0.4122	0.0143	0.3555
P				
0.32 mM	9	25	23	88
1.28 mM	14	34	53	48
Standard error _{0.1} ^z	NS	NS	± 7	NS

^zStandard error for the LSMEANS of P treatments at $\alpha = 0.1$, $n = 8$.

Fig. 1. Plant damage ratings over 4 weeks after inoculating with immature WFT during the reproductive growth stage (Expt. 1). Bars represent SE at each sample date; $n = 4$.

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Table 4. Growth responses and tissue N, P, K, Ca, and Mg concentrations in WFT-inoculated and no-WFT control plants averaged over two sample dates (2 and 4 weeks after inoculation) during the reproductive growth stage (Expt. 1).

Treatment	Ht (cm)	Width (cm)	No. of flower buds	Dry wt (g)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
<i>p</i> value	0.6813	0.0783	0.4152	0.9663	0.0466	0.6596	0.2702	0.2349	0.2821
No-WFT control	11.2	23.1	29.2	3.0	5.54	0.47	2.17	2.02	0.64
WFT-inoculated (10 second-instar nymphs)	11.3	22.6	27.8	3.0	5.40	0.48	2.07	1.94	0.62
LSD _{0.05} ^z	NS	NS	NS	NS	0.13	NS	NS	NS	NS

^zLeast significant difference for comparing WFT-inoculated and no-WFT control plants, *n* = 16 for WFT-inoculated plants and *n* = 8 for no-WFT control plants.

N concentrations represent optimum and luxurious consumption of N as described in Expt. 1. Tissue P in control plants fertilized with 0.32 and 1.28 mM P was 0.37% and 0.77%, respectively (Table 5), which represents adequate tissue P concentrations (e.g., van Iersel et al., 1998; Jonas and Williams, unpublished data). Therefore, as in Expt. 1, test plants were of similar size but provided different diets for WFT.

The relationship between WFT population levels and nutrient treatments was statistically analyzed based on the number of adult, immature, and total WFT (sum of immature and adult WFT) separately at each sample date, as well as over the entire 4-week period. The number of adult WFT and total WFT in plants fertilized with 1.28 mM P was significantly higher than in plants fertilized with 0.32 mM over 4 weeks ($F = 4.0$, $df = 105$, $p = 0.0481$, and $F = 3.03$, $df = 105$, $p = 0.0846$, respectively, $\alpha = 0.1$, Table 6). The number of immature WFT ($F = 2.5$, $df = 105$, $p = 0.1170$, Table 6) showed a similar trend, but the differences were not significant. N application rates had no effect on WFT population levels ($F = 0.03$, $df = 105$, $p = 0.8578$, Table 6).

Because inoculation occurred during the vegetative growth stage, WFT fed on foliage extensively; therefore, compared to the no-WFT control plants, significant damage was observed only 1 week after inoculation ($F = 53.05$, $df = 21$, $p = 0.0008$), and damage ratings generally increased during the 4 weeks after inoculation (Fig. 2). At the end of experiment, some plants received a rating of 5, indicating severe feeding injury that made them unsalable. However, severity of feeding damage did not differ across $N \times P$ treatments ($F = 1.68$, $df = 105$, $p = 0.1975$). When compared with control plants, WFT-inoculated plants were shorter and had smaller width and fewer flower buds; however, dry weight did not differ (Table 7).

Feeding by WFT resulted in significantly lower tissue N, but not tissue P (Table 7). This result is similar to what occurred in Expt. 1 when plants were inoculated during the reproductive stage with immature WFT (Table 4). This result suggests that feeding by WFT might alter the uptake and utilization of N to a greater extent than that of P. However, within a range of commercially acceptable plant growth, tissue P concentration, as a component of the diet of WFT, has a greater impact on the physiology of the WFT than tissue N. WFT feeding did not affect tissue concentrations of K, Ca, or Mg (Table 7).

Damage among nutrient treatment combinations did not differ in either experiment over four sample dates. When comparing damage among nutrient treatment combinations by week, no differences were observed at most sample dates.

Table 5. Growth responses and tissue N and P concentrations in no-WFT control plants averaged over two sample dates (2 and 4 weeks after inoculation) during the vegetative growth stage (Expt. 2).

Treatment	Ht (cm)	Width (cm)	Dry wt (g)	No. of flower buds	N (%)	P (%)
<i>p</i> value ^z						
N	0.1407	0.6393	0.7557	0.6373	0.0002	0.1021
P	0.9806	0.4084	0.8783	0.4195	0.7932	0.0001
8 mM	11.0	16.2	1.07	41.3	4.9	0.53
20 mM	9.4	15.6	1.01	37.9	6.3	0.61
LSD _{0.05} ^y	NS	NS	NS	NS	0.4	NS
0.32 mM	10.2	16.4	1.05	42.5	5.7	0.37
1.28 mM	10.2	15.4	1.03	36.6	5.6	0.77
LSD _{0.05}	NS	NS	NS	NS	NS	0.11

^z $N \times P$ interaction was not significant except for tissue N%, but the pattern of interaction would not affect N treatment effect at either P level.

^yLeast significant difference for comparing two N or P rates at $\alpha = 0.05$, *n* = 8.

Table 6. Number of adult, immature, and total western flower thrips (WFT) on WFT-inoculated plants averaged over four sample dates after inoculation during the vegetative growth stage (Expt. 2).

Treatment	No. of WFT/plant		
	Adult	Immature	Total
<i>p</i> value			
N	0.5571	0.9231	0.8578
P	0.0481	0.1170	0.0846
0.32 mM	17	71	88
1.28 mM	22	90	112
Standard error _{0.1} ^z	±2	NS	±15

^zStandard error for the LSMEANS of P treatments at $\alpha = 0.1$, *n* = 64.

Fig. 2. Plant damage ratings over 4 weeks after inoculating with adult female WFT during the vegetative growth stage (Expt. 2). Bars represent SE at each sample date; *n* = 8.

Therefore, despite a trend of increase in WFT population with increasing foliar P concentration, we did not observe a significant increase in aesthetic damage.

Discussion

It is generally believed that supplementary N in plants results in enhanced health, growth, reproduction, and survival of most

Table 7. Growth responses and tissue N, P, K, Ca, and Mg concentrations in western flower thrips (WFT)-inoculated plants and no-WFT control plants averaged over two sample dates (2 and 4 weeks after inoculation) during the vegetative growth stage (Expt. 2).

Treatment	Ht (cm)	Width (cm)	No. of flower buds	Dry wt (g)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
p value	0.0398	0.0356	0.0058	0.2332	0.0321	0.0633	0.0569	0.4809	0.1111
No-WFT control	10.1	15.8	40	1.04	5.56	0.59	2.61	1.80	0.61
WFT-inoculated (10 female adults)	9.3	14.1	29	0.95	5.39	0.54	2.87	1.76	0.58
LSD _{0.05} ^z	0.5	1.1	4.6	NS	0.2	NS	NS	NS	NS

^zLeast significant difference for comparing WFT-inoculated and no-WFT control plants, n = 32 for WFT-inoculated plants and n = 8 for no-WFT control plants.

arthropod species (Mattson, 1980), including thrips (Ananthakrishnan, 1993). Reports of a positive relationship between phytophagous arthropod response and increased N are often based on experiments where insect responses to plants deficient in N are compared to plants with sufficient or luxurious N concentrations (e.g., Bethke et al., 1987; Schuch et al., 1998; Wermelinger et al., 1985). In our research, a difference in WFT population was not observed between the high versus low N plants, probably because no N-deficient plants were tested. Plants produced by both N regimes were of commercial quality, but contained significantly different foliar N concentrations from optimal to luxurious. These results indicate that within the range of N fertility that produces commercially-acceptable impatiens plants, increasing foliar N concentration does not support a significant increase in WFT populations. From a practical standpoint, this suggests that growers need not be concerned about an enhanced WFT response from over-application of N.

However, feeding by WFT significantly decreased tissue N concentration of impatiens compared to no-WFT control plants in both experiments: tissue N in plants with WFT for 4 weeks was 0.13% to 0.26% lower than control plants at both optimum and luxurious N fertilizer levels. A number of plant responses to feeding by WFT could have contributed to this outcome, including indirect disruption of N uptake, assimilation, and translocation in relation to a reduction in whole-plant photosynthesis.

Plant growth (except for dry weight) was affected by WFT feeding only in Expt. 2, when plants in the vegetative stage were inoculated with adult WFT, so these WFT fed on leaf and meristematic tissue. The rate of photosynthesis is decreased by epidermal feeders such as thrips (Welter, 1989). Individual cases of WFT feeding resulting in reduced photosynthesis have been reported for impatiens (Buntin et al., 1988) and cucumber (*Cucumis sativus* L.) (Hao et al., 2002). Buntin et al. (1988) speculated that mechanical disruption of chlorophyll-containing mesophyll cells occurs by thrips feeding and that this damage is the primary mechanism by which photosynthesis is reduced. Hao et al. (2002) reported that a reduced photosynthetic rate from WFT feeding occurred only after exposure to extremely large populations; therefore, they proposed that a reduction in leaf area was the main mechanism by which thrips feeding reduced whole plant photosynthesis. These mechanisms of photosynthesis reduction are different than reports of stomatal closure caused by other phytophagous feeders such as

spider mites (e.g., DeAngelis et al., 1982).

In Expt. 1, when plants in the reproductive stage were inoculated with immature WFT, plant growth was not smaller in inoculated versus no-WFT control plants. This likely reflects the preferred feeding site in the reproductive stage, which is the nectariferous spur of the flowers. WFT are flower dwellers on many crops as they feed on pollen and nectar (Kirk, 1988). This was observed in our research, where 63% of the total number of WFT were found inside of the nectariferous spurs of the open flowers in Expt. 1. Unlike N, WFT feeding did not decrease tissue concentration of P, K, Ca, or Mg.

The effect of tissue P on arthropod populations has rarely been studied (e.g., Feller, 1995; Rodriguez, 1963; Wooldridge and Harrison, 1968), although P is limited in nature and is an essential macronutrient. In all of the research conducted before 1989, the most common herbivore response to P-fertilized plants was no response (44% of 50 cases), and the second most common response was positive (34%) (Waring and Cobb, 1989). After this, a few studies postulated that a P effect occurred because of changes in secondary metabolites such as phenolics and terpenes. For example, Sun et al. (2000) observed a suppression in the population of pine tip moth [*Rhyacionia frustrana* (Comstock)] in loblolly pine (*Pinus taeda* L.) fertilized with P, which may have been due to increased terpene composition of oleoresin. Research with the phytophagous twospotted spider mite (*Tetranychus urticae* Koch; TSM) indicated that its development and preoviposition period were slightly prolonged with P deficiency, and fecundity increased under moderate P shortage when the N concentration was the highest (Wermelinger et al., 1991).

In our research, there was a strong trend towards increased WFT population growth resulting from increased foliar P concentration. Plants under different treatments had varying P concentration but were of similar size and commercial quality, which suggests that the difference in WFT population was likely due to variable tissue P concentrations as opposed to the increased biomass production common with increasing rate of P fertilization. During feeding by WFT, epidermal cells are rasped apart and liquid contents are sucked up, resulting in collapse of cells surrounding the feeding site. This suggests that P-containing intracellular compounds such as nucleic acids, energy-transfer compounds like ADP and ATP, and P-storage compounds like polyphosphates are consumed by WFT. Since most WFT adults are females (Ananthakrishnan, 1979), an increase in the

number of adults is strongly related to an increase in total WFT. Our research suggests that as tissue P concentration increases and becomes luxurious in plant cells, these plants may be a more beneficial nutrient source for WFT growth and development. Though not with a phytophagous insect, a study evaluating the C to P ratio of an artificial diet of mayflies (*Caenis* sp.) indicated that low C to P ratio food produced more rapid growth (Frost and Elser, 2002).

In both experiments, a wide range of visual damage from WFT feeding was observed over the 4-week period after inoculation. It is not possible to directly compare the results of the two experiments because different WFT life stages were used for inoculation. However, various life stages were present on a plant at the time of sampling due to the short developmental time of this pest. As a general observation, plants inoculated while in the vegetative stage with adults (Expt. 2) exhibited severe damage faster than plants that were inoculated in the reproductive stage with immature WFT (Expt. 1). In fact, plants were unsalable three weeks after vegetative-stage inoculation, but all plants were salable at the end of the production cycle when inoculated in the reproductive stage. This observation suggests that growth stage of the plant should be considered when deciding upon a thrips management program for impatiens. It is important to note, however, that these two experiments occurred during different seasons, and WFT population levels increased faster in Expt. 2, likely due to the warmer temperatures as well as inoculation with adult female WFT as opposed to immature WFT. Even so, concentrated feeding damage on foliage and meristematic tissues were only observed in Expt. 2.

Because aesthetic damage thresholds for ornamental crops are very low, IPM programs typically use low action thresholds. As examples, in one study, two thrips per yellow sticky card per week resulted in initiation of biological control (Jacobsen, 1993); and in another study, 18 thrips per blue sticky card per week were at the lower end of the damage threshold (Frey, 1993). Monitoring and scouting efforts early in the production cycle are most crucial for control of WFT before aesthetic damage occurs. Our experience suggests that damage thresholds for impatiens in the vegetative growth stage should be lower than for plants that already have open flowers. In fact, early-flowering cultivars may provide an advantage of tolerance to WFT compared to cultivars with longer vegetative growth stages.

In the greenhouse industry, P fertilizer has been historically over-applied (Nelson, 1990), raising concerns about pollution associated

with nutrient effluent. Our results provide evidence that growers should manage P fertility to minimize luxurious accumulation of this nutrient because it may support more rapid growth of WFT populations. Nitrogen fertility within the range that produces commercially acceptable impatiens does not impact WFT populations.

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