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## Winter Application of Low-biuret Urea to the Foliage of 'Washington' Navel Orange Increased Yield

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**Abstract.** The objective of this study was to test whether a single winter prebloom foliar application of low-biuret urea would increase the yield of 30-year-old 'Washington' navel orange trees [*Citrus sinensis* (L.) Osbeck] on Troyer citrange rootstock [*C. sinensis* 'Washington' x *Poncirus trifoliata* (L.) Raf.]. All trees received a winter (November to January) soil application of urea (0.5 kg N/tree). Trees were maintained under irrigation or irrigation was withheld from 1 Oct. to 1 Mar. To determine the optimal time for foliar urea application, trees in both irrigation main plots received one application of low-biuret urea in mid-November, mid-December, mid-January, or mid-February applied at a rate of 0.16 kg N/tree. There was a set of control trees that only received the soil application of urea. Trees receiving foliar-applied urea in mid-January or mid-February, independent of irrigation treatment, had significantly greater yield and fruit number per tree each year than the control trees for 3 consecutive years. The number of fruit with diameters of 6.1 to 8.0 cm increased significantly as yield increased ( $r^2 = 0.88$ ). Withholding irrigation from 1 Oct. to 1 Mar. had a negative impact on yield. Annual winter application of low-biuret urea to the foliage did not significantly increase leaf total N at the end of 3 years.

It is well established that water deficit during the summer induces flower formation in certain lemon (*Citrus limon*) and lime (*Citrus aurantifolia*) cultivars. A common orchard management practice in lemon culture in Sicily, Italy, is *forzatura*—forcing lemon flowers in late summer (August to September) by withholding irrigation during the summer (June to July) until the leaves have wilted and then applying N fertilizer to the soil when rewatering the trees (Hodgson, 1967). The bloom occurs shortly after the resumption of irrigation. The crop, called *verdelli* due to the light green-yellow color of the lemons, is harvested the following summer when prices are typically high (Barbera et al., 1981; Hodgson, 1967). The common practice of supplying N to the soil at the end of the stress-induction provided early evidence that N might be involved in flowering. In a review of *forzatura*, Monselise (1985) concluded that the magnitude of stress-induced flowering increased when N was supplied at the end of the stress period.

In tropical areas with distinct rainy and dry seasons, water-deficit stress substitutes for low temperature in citrus floral induction (Cassin et al., 1969; Reuther and Rios-Castano, 1969; Reuther, 1973). According to Cassin et al. (1969), citrus flowering occurs  $\approx 20$  to 28 days after the first effective rain or irrigation. Southwick and Davenport (1986) reported that 2 weeks of withholding water, resulting in plants with mean predawn leaf water potentials of  $-0.9$  MPa and midday leaf water potentials of  $-2.25$  MPa, sufficiently induced flowering in 'Tahiti' lime. Severe water deficit resulting in  $-3$  MPa for 20 days followed by 40 days of moderate water deficit ( $-2$  MPa) or moderate water deficit ( $-2$  MPa) for 50 days followed by foliar application of low-biuret urea induced flower-

ing in 16-year-old 'Frost Lisbon' lemon trees. However, severe water deficit for only 30 days ( $-3$  MPa) did not effectively induce flowering. Flowering was maximum at 4 weeks after resuming full irrigation (Lovatt et al., 1988a, 1988b). Mild soil moisture stress followed by irrigation increased the intensity of flushing and flowering in acid lime species but severe moisture stress was detrimental. A predawn relative water content of 91.0% to 93.0% seemed to be the optimum level of stress for inducing flowering in acid lime (Singh and Chadha, 1988).

The relationship between flowering and different forms of fertilizers was studied by Grasmanis and Leeper (1967), who demonstrated that hydroponically cultured 'Jonathan' apple trees fertilized with ammonium, alone or with nitrate, flowered earlier and produced more flowers among the total buds than trees receiving nitrate alone. Consistent with the shift from vegetative to floral buds, vegetative growth was reduced when ammonium was provided. When trees were given only nitrate during the year except for a 2-month interval in December and January during which ammonium nitrate was supplied, vegetative growth was not reduced but the total number of flowers in the following spring was three times as great as with nitrate alone. Even exposure of only 24 h to ammonium in January or as late as February significantly increased flowering over nitrate alone (Grasmanis and Edwards, 1974). Subsequently, Edwards (1986) demonstrated that the brief exposure to ammonium resulted in a greater concentration of arginine and that polyamine infusion also increased flowering in apple. In addition, Costa and Bagni (1983) and Costa et al. (1984, 1986) demonstrated that exogenous application of putrescine to apple trees during early bloom increased fruit growth during cell division, with a concomitant increase in fruit set and yield.

Research with citrus has provided evidence of a similar relationship between ammonium and its metabolites and flowering and fruit set. Lovatt et al. (1988a, 1988b) quantified leaf concentrations of several C and N compounds before, during, and after low-temperature or water-deficit stress treatments that were designed to induce flowering in 5-year-old rooted cuttings of 'Washington' navel orange and commercially producing 16-year-old 'Frost Lisbon' lemon trees, respectively. Total flower number and total number of floral shoots per tree were significantly correlated with  $\text{NH}_3\text{-NH}_4^+$  accumulation in the leaves during induction. No changes were observed in leaf concentrations of total N, nitrate, glucose, or starch during or after the

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two flower-induction treatments.

A physiological relationship between tree  $\text{NH}_3\text{-NH}_4^+$  status and flowering was demonstrated (Lovatt et al., 1988a, 1988b). Trees were subjected to minimal stress, i.e., 4 instead of 8 weeks of low-temperature treatment or deficit irrigation instead of withholding irrigation, treatment that does not usually result in significant flower production. At the end of the low-temperature stress treatment or half-way through the water-deficit stress treatment, half of the trees received a foliar application of low-biuret urea (0.25% biuret). This resulted in an increase in leaf  $\text{NH}_3\text{-NH}_4^+$  content and the number of floral shoots per tree and flowers per shoot, but not the number of vegetative shoots produced.

Apical flowers initiated in response to stress also exhibited maximum tissue concentrations of ammonia and putrescine and maximum activity of the *de novo* arginine biosynthetic pathway 1 week after the end of stress treatment. All three criteria decreased similarly as flowers developed through petal fall (Sagee and Lovatt, 1991). Developing flowers and early postpetal-fall fruit borne in the terminal position of the leafy inflorescences had significantly greater polyamine content, faster growth rates, and exhibited a greater percent fruit set than those borne in the terminal position of leafless inflorescences (Lovatt et al., 1992).

Taken together, the results of the research with apple and citrus support the hypothesis that ammonia, or its metabolites, may have a positive influence on flower production and on subsequent ovary development and set.

With regard to N fertilization of citrus, using foliar-applied urea was demonstrated in the early 1960s to be as efficacious as nine other N sources supplied to the soil in maintaining yield of orange trees (Leonard et al., 1961). Embleton and Jones (1974) provided evidence that, kilogram for kilogram, foliar-applied N was as effective as soil-applied N for producing citrus. For sweet oranges, they proposed that maximum nutritionally attainable yields were obtained with annual application of 0.45 to 0.65 kg N/tree, regardless of application method. Foliar application of N fertilizer to citrus was not widely adopted commercially due to the limits in the amount of N that can be applied in a single application, necessitating three to six foliar sprays each year to provide the recommended annual N rate. This has created the perception that foliar N fertilization is more expensive because several applications are required to maintain yield. In contrast, earlier results of Sharples and Hilgeman (1969) suggested that urea applied to the foliage at the proper time might beneficially affect yield. They were able to obtain yields of 'Valencia' oranges over 7 years with only 0.23 kg N/tree split between two foliar applications of urea, one in February and a second in late April to early May, that were statistically equal to yields obtained with 0.45 or 0.91 kg N/tree as ammonium nitrate supplied to the soil. In addition, Embleton and Jones (1978) and Embleton et al. (1986) documented that foliar N application substantially reduced nitrate pollution of groundwater, even when used to replace soil-applied N only partially.

The present study was undertaken to test the efficacy of and determine the optimal time for applying ammonia as a winter prebloom spray of low-biuret urea to the foliage, i.e., just before or during flower initiation, to maximize yield of 30-year-old 'Washington' navel orange scions on Troyer citrange rootstock. In addition, we tested the use of water-deficit stress as an additional method of increasing the  $\text{NH}_3\text{-NH}_4^+$  status of trees to increase flowering, fruit set, and yield.

## Materials and Methods

*Chemicals.* Unocal Plus (Unocal Corp., Brea, Calif.) liquid

low-biuret (20% N, 0.1% biuret) urea was used for foliar application and granular low-biuret (46% N, 0.25% biuret) urea (BP Chemicals, Lima, Ohio) was used for soil application. All other chemicals were purchased from Sigma (St. Louis).

*Plant material.* Thirty-year-old 'Washington' navel orange trees on Troyer citrange rootstock located at the Citrus Research Center and Agricultural Experiment Station, Univ. of California, Riverside, were used. Tree density was 237 trees/ha. In previous years, the trees produced yields similar to the average annual production for southern California navel orange trees, i.e., 30 t·ha<sup>-1</sup> (California Agricultural Statistics Service, 1986–91). All trees used in the experiment were shown by leaf analysis to have sufficient N (2.68%) at the initiation of the study according to the standards of Embleton et al. (1973). The experimental design was a split plot, with irrigation treatments as main plots and N treatments as subplots. All trees received 0.5 kg N/tree as urea (granules, 0.25% biuret) applied to the soil on 18 Jan. 1988, 5 Dec. 1989, and 11 Nov. 1990. The main plots were replicated twelve times and consisted of two irrigation treatments: 1) standard commercial practice (well-watered) or 2) water withheld from 1 Oct. to 1 Mar. Trees were furrow-irrigated every 3 weeks for 24 or 48 h (24,243 liters·h<sup>-1</sup>·ha<sup>-1</sup>). The subplots consisted of five N treatments. Treatments 1 through 4 involved a single foliar application of low-biuret urea in mid-November, mid-December, mid-January, or mid-February, respectively. Treatment 5 was the control in which trees received no foliar N application. There were 12 individual tree replicates for each N treatment per irrigation treatment (a total of 120 data trees). Low-biuret urea was applied to the foliage to the point of runoff at a final concentration of 0.5% N (3.7 kg N/662 liters water, i.e., ≈0.16 kg N in 28 liters per tree) as recommended by Embleton et al. (1973).

Fruit were harvested on 23 to 24 Jan. 1990, 4 to 5 Feb. 1991, and 25 to 27 Feb. 1992. Total fruit yield per tree and total fruit number per tree were determined. Fruit diameters were measured for individual fruit randomly selected from different tree quadrants and grouped into three subsamples, which consisted of 25 fruit each, representing 5% to 30% of the total number of fruit per tree for the 3 years of the study. These data were used to estimate fruit size distribution in the following categories: 1) fruit with a diameter of 7.0 to 8.0 cm (packing carton sizes 88 and 72); 2) fruit with a diameter of 6.1 to 6.9 cm (packing carton sizes 138 and 113); and 3) fruit with a diameter of 5.2 to 6.0 cm (packing carton sizes 180 and 163).

*Physiological parameters.* To determine leaf total N concentration, 40 five-month-old, spring-cycle leaves from nonfruiting terminals were collected per tree as described by Embleton et al. (1973) in September 1988–92, washed with soapy water, and rinsed thoroughly with distilled water. The leaves were oven-dried at 60°C and ground in a Wiley mill to a size fine enough to pass through a 40-mesh screen. Total N was determined for a 25-mg sample with 12 replications per N treatment within each irrigation treatment using the conventional micro-Kjeldahl method.

Leaf  $\text{NH}_3\text{-NH}_4^+$  concentration was monitored from 1 Oct. to 1 Mar. for each year of the study. Mature leaves (40 per tree) from the spring flush were collected monthly 1 to 2 days before urea application and ≈30 days after urea application for the treated trees. Leaves were washed, oven-dried, and ground as described above. A 500-mg (dry weight) sample was homogenized with a tissue homogenizer (Polytron, PCU; Brinkmann Instruments, Westbury, NY) in 6 ml of 10% trichloroacetic acid (TCA). The probe was rinsed with 4 ml of 10% TCA, which was added to the homogenate. The homogenate was centrifuged at 10,000× g at 4°C for 10 min and filtered through nylon and glass fiber filters. The  $\text{NH}_4^+$  content of

the acid-soluble filtrate containing the combined pool of  $\text{NH}_3\text{-NH}_4^+$  was determined on 12 replications per N treatment for each irrigation treatment using an inorganic N analyzer (Alltech, Deerfield, Ill.) (Carlson, 1978). The assay was linear for  $\text{NH}_4^+$  concentrations from 0 to 100  $\mu\text{g}\cdot\text{ml}^{-1}$ . Samples were diluted to give values in this range.

Tree predawn water potential was measured with a pressure chamber every third week just before irrigation. Two to three water potential measurements were made on 12 trees per irrigation treatment using fully expanded mature leaves. Predawn water potential is presented as the mean  $\pm$ SE,  $n = 12$ .

**Statistical analysis.** Data were subjected to a factorial analysis of variance using SAS's general linear model procedure (SAS Institute, 1988), with N treatments as subplots and irrigation treatments as main plots (Tables 2–7). However, repeated measure analysis (SAS Institute, 1988) was used to test effect of N and irrigation treatments on fruit yield and number over the years of the study (Table 1). Mean separation was accomplished with Duncan's multiple range test at  $P \leq 0.05$ .

## Results

### Yield response to winter foliar application of low-biuret urea.

The combined effects of N and irrigation treatments over the 3 years of the experiment are shown in Table 1. When averaged over irrigation treatments, those trees that had received a foliar application of low-biuret urea in November, December, January, or February had significantly more yield and fruit number per tree than the control trees receiving only soil-applied urea. The significant year  $\times$  N interaction on yield was due to the freeze year, since excluding the yield data for that year from the analysis eliminated the interaction. The results also demonstrated that the irrigation treatments had a significant effect on yield and fruit size. However, there was no N  $\times$  irrigation treatment interaction. For fruit number, there was a significant N  $\times$  irrigation treatment  $\times$  year interaction, which was not eliminated by disregarding the data for the freeze year. When averaged over the 3 years of the study, there were significant positive correlations between yield and number of fruit of commercially desirable sizes, i.e., fruit with diameters of 6.1 to

8.0 cm (Fig. 1). In contrast, the number of smaller fruit, i.e. fruit with diameters of 5.2 to 6.0 cm, did not significantly increase similarly with yield ( $r^2 = 0.30$ ).

In each year of the study, there were no significant N  $\times$  irrigation treatment interactions on yield and fruit number per tree (Table 2, 3). In all 3 years of the study, trees receiving one application of low-biuret urea to the foliage in mid-January or mid-February, independent of irrigation treatment, had significantly greater yield per tree than the control trees receiving only soil-applied urea (Table 2). Only trees receiving a foliar application of urea in mid-January had a significantly greater number of fruit per tree than the control trees for all 3 years of the study (Table 3). Increased yield resulting from the winter foliar application of urea was not associated with a reduced number of larger fruit, i.e., those with diameters of 7.0 to 8.0 cm, in any year (Table 4).

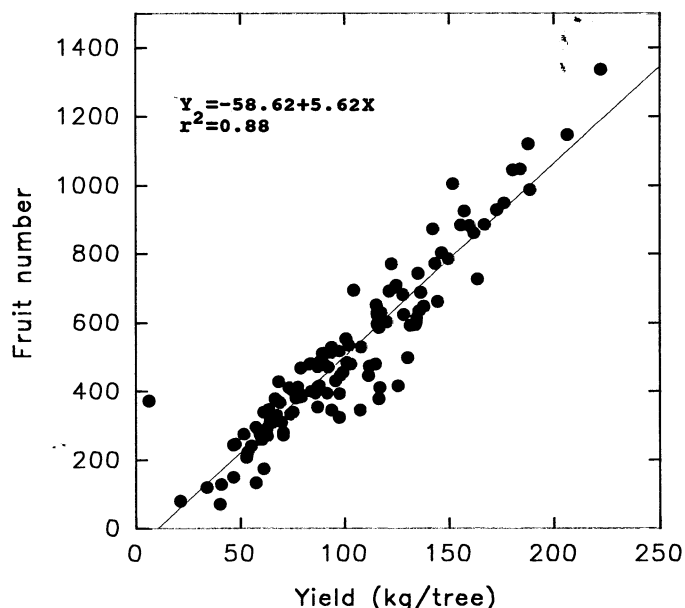


Fig. 1. Yield (kg/tree) vs. number of fruit with diameters of 6.1.0 to 8.0 cm per tree averaged over the 3 years of the study for each tree replicate ( $n = 120$ ).

Table 1. Effects of foliar application of low-biuret urea and irrigation treatments across years on yield per tree, fruit number per tree, and number of fruit with diameters of 7.0 to 8.0 cm and 6.1 to 6.9 cm.

Month urea was applied (N)	Yield (kg/tree)	Fruit no./tree		
		All sizes	7.0–8.0 cm	6.1–6.9 cm
None (control)	85.3 b <sup>z</sup>	542 b	172 a	274 a
November	101.5 a	657 a	188 a	314 a
December	102.5 a	661 a	211 a	316 a
January	112.6 a	761 a	190 a	358 a
February	106.8 a	708 a	198 a	325 a
Significance of F test				
N	***	**	NS	NS
Irrigation (I)	****	****	***	****
N $\times$ I	NS	NS	NS	NS
Year (Y)	****	****	****	****
N $\times$ Y	*	***	NS	NS
I $\times$ Y	****	****	****	****
N $\times$ I $\times$ Y	NS	*	NS	NS

<sup>z</sup>Means within a column with the same letter are not significantly different by Duncan's multiple range test at  $P = 0.05$ .

NS, \*, \*\*, \*\*\*, \*\*\*\* Nonsignificant or significant at  $P = 0.05, 0.01, 0.001, \text{ or } 0.0001$ , respectively.

Table 2. Effect of a single foliar application of low-biuret urea and irrigation treatments on yield per tree of 'Washington' navel orange.

Treatment	Year		
	1989–90	1990–91	1991–92
Month urea was applied (N)	kg fruit/tree		
None (control)	109.4 b <sup>z</sup>	31.8 c	116.2 b
November	124.6 a	41.7 abc	140.1 a
December	128.8 a	37.7 bc	142.9 a
January	132.4 a	48.4 a	159.1 a
February	126.9 a	45.5 ab	149.9 a
	*	*	**
Irrigation (I)	kg fruit/tree		
Irrigated	131.6 a	69.4 a	173.9 a
Nonirrigated	115.8 a	12.6 b	107.7 b
	NS	***	***
N $\times$ I	NS	NS	NS

<sup>z</sup>Means within a column with the same letter are not significantly different by Duncan's multiple range test at  $P = 0.05$ .

NS, \*, \*\*, \*\*\*, \*\*\*\* Nonsignificant or significant at  $P = 0.05, 0.01, \text{ or } 0.001$  respectively.

Table 3. Effect of a single foliar application of low-biuret urea and irrigation treatments on total fruit number per tree of 'Washington' navel orange.

Treatment	Year		
	1989-90	1990-91	1991-92
Month urea was applied (N)	Fruit no./tree		
None (control)	612 b <sup>z</sup>	195 b	821 c
November	715 a	248 ab	1009 bc
December	734 a	213 b	1037 ab
January	767 a	295 a	1221 a
February	719 a	270 ab	1135 ab
	*	*	**
Irrigation (I)	Fruit no./tree		
Irrigated	732 a	419 a	1440 a
Nonirrigated	688 a	69 b	649 b
	NS	***	***
N × I	NS	NS	NS

<sup>z</sup>Means within a column with the same letter are not significantly different by Duncan's multiple range test at  $P = 0.05$ .

NS,\*,\*\*,\*\*\* Nonsignificant or significant at  $P = 0.05, 0.01, \text{ or } 0.001$  respectively.

Table 4. Effect of a single foliar application of low-biuret urea and irrigation treatments on number of fruit with diameters 7.0 to 8.0 cm per tree of 'Washington' navel orange.

Treatment	Year		
	1989-90	1990-91	1991-92
Month urea was applied (N)	Fruit no./tree		
None (control)	243 a <sup>z</sup>	81 a	194 a
November	256 a	100 a	208 a
December	294 a	114 a	227 a
January	260 a	119 a	192 a
February	269 a	115 a	211 a
	NS	NS	NS
Irrigation (I)	Fruit no./tree		
Irrigated	303 a	177 a	150 a
Nonirrigated	227 b	33 b	263 b
	*	****	**
N × I	NS	NS	*

<sup>z</sup>Means within a column with the same letter are not significantly different by Duncan's multiple range test at  $P = 0.05$ .

NS,\*,\*\*,\*\*\*\* Nonsignificant or significant at  $P = 0.05, 0.01, \text{ or } 0.0001$  respectively.

For the first year of the experiment (1989-90), specific time of urea application did not significantly affect yield. Trees, independent of irrigation treatments, receiving a foliar application of low-biuret urea had significantly greater yield (Table 2) and fruit number per tree (Table 3) and the number of fruit of commercially valuable size was not reduced (Tables 4 and 5) compared to control trees receiving only soil-applied urea (Tables 4 and 5). The yield was significantly reduced in the second year of the experiment (1990-91) due to a freeze that occurred on 23 Dec. 1990. In this year, the month during which the urea was applied to the foliage had a statistically significant effect on yield. Independent of irrigation treatments, only trees receiving a foliar application of urea in mid-January or mid-February had more yield per tree (52% and 43% more, respectively) than control trees receiving soil-applied

urea. Also, trees receiving foliar-applied urea in mid-January had 51% more fruit per tree than trees receiving soil-applied urea (Table 3). Increased yield resulting from foliar-application of urea did not reduce the number of fruit in the 6.1- to 8.0-cm size category (Tables 4 and 5). Also, independent of irrigation treatments, trees receiving foliar low-biuret urea in mid-January had the greatest yield and fruit number per tree and more fruit of economically valuable size per tree, i.e., those with diameters of 6.1 to 8.0 cm (Tables 4 and 5).

The results of the 1991-92 season demonstrated that applying urea to the foliage in mid-January or mid-February significantly increased yield and fruit number per tree compared with trees receiving soil-applied urea. All trees, independent of irrigation treatments, receiving foliar application of low-biuret urea had significantly greater yield per tree than the control trees (Table 2). Trees receiving a foliar application of urea in mid-November, mid-December, mid-January, or mid-February had 24 kg (21%), 26 kg (22%), 43 kg (37%), and 34 kg (29%) more yield per tree, respectively, than the control trees not receiving a foliar application of urea. Furthermore, trees receiving a foliar application of urea in mid-December, mid-January, or mid-February had a 26%, 49%, and 38% increase in fruit number per tree than trees not receiving foliar urea application (Table 3). Increased yield resulting from the winter foliar application of urea was not associated with a reduced number of fruit of desirable size (Tables 4 and 5).

*Effect of irrigation treatments on yield.* During the first year of the study (1989-90), withholding irrigation from 1 Oct. 1988 to 1 Mar. 1989 did not significantly reduce predawn water potential except in November, presumably due to precipitation in December through March. These trees were harvested on 23 to 24 Jan. 1990. Despite the fact that the nonirrigated trees exhibited substantial water-deficit stress ( $-2.5 \pm 0.14$  MPa) in December 1989, there was no significant difference in yield or fruit number per tree between trees in the two irrigation treatments in 1989-90 (Tables 2 and 3). However, there was a trend toward increased yield and fruit number per tree for irrigated trees. Moreover, irrigated trees had significantly more fruit per tree with a diameter of 7.0 to 8.0 cm, equaling about one-half box more fruit per tree in 1989-90 (Table 4).

In the second year of the study (1990-91), the nonirrigated trees experienced substantial water-deficit stress just before flower initiation in February 1990 ( $-2.32 \pm 0.17$  MPa). At the time of the freeze in December 1990, these trees were substantially stressed ( $-2.47 \pm 0.16$  MPa). When the trees were harvested in February 1991, they were stressed ( $-2.62 \pm 0.22$  MPa). As a result for 1990-91, yield and fruit number were significantly greater for irrigated vs. nonirrigated trees (Tables 2 and 3). Irrigated trees had significantly more fruit per tree with diameters from 7.0 to 8.0 cm (Table 4) and 6.1 to 6.9 cm (Table 5) in 1990-91.

In the third year of the study (1991-92), the nonirrigated trees had a predawn water potential of  $-2.47 \pm 0.16$  MPa in December 1990 and  $-2.62 \pm 0.22$  MPa in February 1991. Irrigation was not withheld from 1 Oct. 1991 through 1 Mar. 1992, so any effect on yield was due to prebloom treatments. Yield and fruit number for irrigated trees were significantly greater than for nonirrigated trees (Tables 2 and 3). In this year, there was a N × irrigation treatment interaction on the number of fruit with diameters of 7.0 to 8.0 cm (Table 4). Irrigated trees that received a single foliar application of low-biuret urea in mid-December, mid-January, or mid-February had significantly more fruit with diameters of 7.0 to 8.0 cm than any of the other treatments (Table 4). No such interaction was observed for fruit with diameters of 6.1 to 6.9 cm (Table 5). Moreover, there was no irrigation × N treatment interaction in the

Table 5. Effect of a single foliar application of low-biuret urea and irrigation treatments on number of fruit with diameters of 6.1 to 6.9 cm per tree of 'Washington' navel orange.

Treatment	Year		
	1989-90	1990-91	1991-92
Month urea was applied (N)	Fruit no./tree		
None (control)	297 a <sup>z</sup>	103 a	422 a
November	325 a	104 a	513 a
December	355 a	72 a	520 a
January	394 a	129 a	552 a
February	341 a	109 a	523 a
	NS	NS	NS
Irrigation (I)			
Irrigated	350 a	185 a	739 a
Nonirrigated	336 a	21 b	272 b
	NS	****	****
N × I	NS	NS	NS

<sup>z</sup>Means within a column with the same letter are not significantly different by Duncan's multiple range test at  $P = 0.05$ .

NS,\*,\*\*,\*\*\*\*Nonsignificant or significant at  $P = 0.05, 0.01, \text{ or } 0.0001$  respectively.

Table 6. Leaf  $\text{NH}_3\text{-NH}_4^+$  concentration of irrigated and nonirrigated 'Washington' navel orange trees 30 days after foliar urea application (1990-91).

Month urea was applied	Month sampled	Irrigation <sup>y</sup>	Leaf $\text{NH}_3\text{-NH}_4^+$ ( $\mu\text{g}\cdot\text{g}^{-1}$ dry wt) <sup>z</sup>	
			No urea (control)	+Urea <sup>x</sup>
November	December	-	132 ± 36	136 ± 30
		+	135 ± 17	155 ± 33
December	January	-	53 ± 7	55 ± 11
		+	73 ± 7	72 ± 15
January	February	-	103 ± 9	98 ± 8
		+	83 ± 14	96 ± 13
February	March	-	71 ± 7	72 ± 12
		+	94 ± 11	92 ± 13

<sup>z</sup>All trees received 0.5 kg N applied to the soil on 11 Nov. 1990. Values represent the means of 12 replicate trees per treatment ±SE.

<sup>y</sup>Nonirrigated (-), water withheld from 1 Oct. to 1 Mar., or irrigated (+).

<sup>x</sup>Trees received low-biuret urea (0.16 kg N, Unocal Plus, 0.01%).

Table 7. Effect of annual foliar application of low-biuret urea on leaf total N concentration at the end of the 3-year study.<sup>z</sup>

Month urea was applied					
November	December	January	February	Control	Significance
2.61 a	2.62 a	2.56 a	2.61 a	2.50 a	NS

<sup>z</sup>Five-month-old spring cycle leaves from nonfruiting terminals collected in September 1992 were used in the analysis.

NSNonsignificant at  $P = 0.05$

first and second year of the study with regard to fruit of either size category (Tables 4 and 5).

*Tree N status.* No differences were observed in leaf  $\text{NH}_3\text{-NH}_4^+$  concentration between control trees and trees that received foliar-applied low-biuret urea in either irrigation treatment (Table 6). The effect of irrigation treatments on leaf  $\text{NH}_3\text{-NH}_4^+$  was inconsistent. For trees maintained under irrigation, leaf  $\text{NH}_3\text{-NH}_4^+$  concentration measured in January in the control trees and the trees

that received foliar-applied low-biuret urea in December and sampled in January was reduced by 46% and 53% compared to leaf  $\text{NH}_3\text{-NH}_4^+$  concentration of trees receiving foliar-applied urea in November and sampled in December, respectively. Under water stress, leaf  $\text{NH}_3\text{-NH}_4^+$  concentration was reduced ≈60% in the control trees and in the trees that received a foliar application of low-biuret urea in December and were sampled in January compared to trees sampled in December. No increase in leaf  $\text{NH}_3\text{-NH}_4^+$  concentration was detected in response to foliar application of urea in the other years of the study.

All trees used in the study had N levels within the range considered optimal for navel orange production in southern California (Embleton et al., 1973) at the beginning of each year of the study. These values were not significantly different from the initial level (data not shown). Thus, despite foliar application of low-biuret urea for 3 consecutive years, leaf total N was not significantly different from control trees receiving only soil-applied urea (Table 7) and not significantly different from the initial concentration. Irrigation and N × irrigation did not significantly affect leaf total N concentration.

## Discussion

The unique feature of the approach used in this research was the winter application of a relatively high rate of urea to the foliage (0.16 kg N/tree), ≈25% to 35% of the annual N required by navel orange for maximum yield (Embleton and Jones, 1974). The winter application of foliar low-biuret urea was intended to replace an equivalent amount of N applied to the soil. However, the arrangements of trees along the irrigation furrows compromised our original intent, and 0.5 kg N/tree was applied in winter to all trees via the soil. Nitrogen is applied to the soil in the winter in California to coincide with the winter rains, but there has been considerable speculation on the amount of this N that is actually used by the citrus tree. Results of the study reported here provide evidence consistent with the interpretation that the yield increases obtained depended on the timing of the prebloom application of urea to the foliage. Only the mid-January and the mid-February applications of low-biuret urea significantly increased yield per tree above the control trees receiving soil-applied urea in every year of the study. With regard to fruit number per tree, there was an effect due to timing of the foliar application of low-biuret urea. Only the mid-January foliar application of low-biuret urea significantly increased the number of fruit per tree over the control trees for each of the 3 years. Mid-February or mid-December foliar applications of low-biuret urea significantly increased the number of fruit per tree in 2 years of the study, while the mid-November application of low-biuret urea significantly increased the number of fruit per tree over that of the control trees receiving only soil-applied urea in only 1 year of the study. Thus, the yield increases obtained in this study are not likely the result of improved N status of the tree by the additional N supplied to the foliage, because all trees receiving a foliar application of low-biuret urea did not exhibit increased yield and fruit number per tree. In addition, all trees were N sufficient at the start of the experiment, since they had an average leaf total N level of 2.68%. Total N concentration of the leaves did not increase significantly in response to the three annual foliar applications of low-biuret urea compared to that of the control trees receiving only soil-applied urea. At the end of the study, leaf total N was not different from that at the start of the experiment and remained at a level considered optimum for navel oranges for California (Embleton, 1973). In addition, there was no correlation between leaf total N concentra-

tion and yield (data not shown). The lack of correlation between leaf total N concentration and yield has been reported previously. In a 7-year experiment comparing foliar urea and soil-applied N, Sharples and Hilgeman (1969) demonstrated a correlation between leaf total N concentration and yield in only 1 year. Leonard et al. (1961) could show no correlation between leaf N concentration and yield in their experiment, which compared foliar application of urea with nine sources of N supplied to the soil. In addition, we could not measure differences in leaf  $\text{NH}_3\text{-NH}_4^+$  concentration between the control trees and trees that received a foliar application of low-biuret urea 30 days after application, likely due to the fact that 30 days was too long a period after the application. Subsequent research in our laboratory indicated that the  $\text{NH}_3\text{-NH}_4^+$  level remained elevated for  $\approx 1$  week after urea application and reached the maximum level within 3 days of application. The reduced leaf  $\text{NH}_3\text{-NH}_4^+$  concentration observed in January for control trees or trees that received a foliar application of low-biuret urea in December is attributed to the freeze that occurred in December 1990. The effects of the freeze on subsequent leaf N metabolism is unknown. In general, it was difficult to distinguish the effects of providing low-biuret urea to the foliage from those of the environment, including irrigation treatments and precipitation, on leaf  $\text{NH}_3\text{-NH}_4^+$  concentration. Attempts to correlate yield and leaf  $\text{NH}_3\text{-NH}_4^+$  concentration were compromised by these factors.

Whether the yield response observed in this study is the result of improving the N status of the trees at a critical time in their phenology or to the specific effect of providing ammonia at the appropriate time to stimulate flowering and/or enhance fruit set as suggested by previous research with apples (Edwards, 1986; Grasmanis and Edwards, 1974) and citrus (Lovatt et al., 1988a, 1988b; Sagee and Lovatt, 1991) remains to be determined. From the results of the current field experiment, it cannot be ascertained whether the mid-January or mid-February foliar applications of low-biuret urea increased flowering; it is clear that they increased fruit set. In a previous study, a single foliar application of low-biuret urea to 'Frost Lisbon' lemon trees induced to flower by water-deficit stress (about  $\approx 2.5$  MPa predawn water potential maintained by deficit irrigation) increased flowering, fruit set, and yield compared to the trees equivalently stressed but not receiving urea (Lovatt et al., 1988a, 1988b).

It is well documented (Barbera and Carimi, 1988; Barbera et al., 1981; Lovatt et al., 1988a, 1988b; Southwick and Davenport, 1986, 1987) that water-deficit stress promotes flowering in *Citrus* species. However, withholding irrigation from 1 Oct. through 1 Mar. generally had a negative impact on yield in all 3 years of this study. Even in the first year of the study in which no significant differences in tree predawn water potential were detected and no significant differences in yield per tree or fruit number per tree were obtained between irrigation treatments, there was a significant reduction in the number of fruit with diameters of 7.0 to 8.0 cm and 6.1 to 6.9 cm due to withholding irrigation. In years 2 and 3, withholding irrigation from 1 Oct. to 1 Mar. resulted in substantial water-deficit stress in December and February. In both years, predawn water potentials were about  $\approx 2.5$  MPa. These trees suffered a greater loss (83%) of their harvestable crop due to the freeze of December 1990 and produced 50% less fruit the following year than irrigated trees. Further experimentation is necessary to determine whether using water-deficit stress in October to reduce the fall flush of foliage and increase carbohydrate storage is a viable method for improving flowering, fruit set and yield. Using water-deficit stress beyond December is unlikely to be of any commercial value.

It must be noted that there were no N  $\times$  irrigation treatment

interactions with regard to yield and fruit number and that the mid-January and mid-February foliar applications of low-biuret urea increased yield over that of the control trees receiving only soil-applied urea whether trees were irrigated or not.

The results of this study demonstrated that a properly timed winter prebloom application of low-biuret urea to the foliage of 'Washington' navel orange increased yield without decreasing the number of fruit with diameters of 7.0 to 8.0 or 6.1 to 6.9 or increasing the number of small fruit with diameters of 5.2 to 6.0 cm. Cost-benefit analysis indicated that this management strategy is economically viable (Ali and Lovatt, 1992) and, because it provides via the foliage 25% to 35% of the N required annually by sweet oranges (Embleton and Jones, 1974), it is environmentally sound. Whether or not the yield of other citrus varieties might be increased by a properly timed prebloom spray of low-biuret urea will be addressed in future research.

### Literature Cited

- Ali, A. G. and C.J. Lovatt. 1992. Scientific rationale and economic incentives: Winter application of foliar urea. *Citrograph* 78:7-9.
- Barbera, G. and F. Carimi. 1988. Effects of different levels of water stress on yield and quality of lemon trees. *Proc. 6th Intl. Citrus Congr.* 2:717-722.
- Barbera, G., G. Fatta Del Bosco, and G. Occorso. 1981. Some aspects of water stress physiology on forced lemon (*Citrus limon* Burm) trees. *Proc. Intl. Soc. Citricult.* 2:522-523.
- California Agricultural Statistics Services. California fruit and nut acreage, Sacramento, 28p. 1986-91.
- Carlson, R.M. 1978. Automated separation and conductimetric determination of ammonia and dissolved carbon dioxide. *Ann. Chem.* 50:1528.
- Cassin, J., B. Bourdeaut, F. Fougue, V. Furin, J.P. Gaillard, J. Le Bourdelles, C. Montigut, and C. Monevil. 1969. The influence of climate upon blooming of citrus in tropical areas. *Proc. 1st Intl. Citrus Symp.* 1:315-323.
- Costa, G. and N. Bagni. 1983. Effects of polyamines on fruit-set of apple. *HortScience* 18:59-61.
- Costa, G., R. Baraldi, and N. Bagni. 1984. Influence of putrescine on fruit set of apple (cv. 'Ruby Spur'). *Acta Hort.* 149:189-191.
- Costa, G., R. Biasi, and N. Bagni. 1986. Effect of putrescine on fruiting performance of apple (cv. Hi Early). *Acta Hort.* 179:355-361.
- Edwards, G.R. 1986. Ammonia, arginine, polyamines and flower initiation in apple. *Acta Hort.* 179:363.
- Embleton, T.W. and W.W. Jones. 1974. Foliar-applied nitrogen for citrus fertilization. *J. Environ. Quality* 3:388-392.
- Embleton, T.W. and W.W. Jones. 1978. Nitrogen fertilizer management programs, nitrate-pollution potential, and orange productivity, p. 275-295. In: D.R. Nielsen and J.G. MacDonald (eds.). *Nitrogen in the environment*. vol 1. Academic Press, New York.
- Embleton, T.W., W.W. Jones, C.K. Labanauskas, and W.J. Reuther. 1973. Leaf analysis as a diagnostic tool and guide to fertilization, p. 183-211. In: W.J. Reuther (ed.). *The citrus industry*. vol. 3. Univ. of California, Div. of Agr. Sci., Berkeley.
- Embleton, T.W., M. Matsumura, L.H. Stolzy, D.A. Devitt, W.W. Jones, R. El-Motaium, and L.L. Summers. 1986. Citrus nitrogen fertilizer management, groundwater pollution, soil salinity and nitrogen balance. *Applied Agr. Res.* 1:57-64.
- Hodgson, R.W. 1967. Horticultural varieties of citrus, p. 431-591. In: W.R. Reuther, H.J. Webber, and L.D. Batchelor (eds.). *The citrus industry*. vol. 1. Univ. of California, Div. of Agr. Sci., Berkeley.
- Grasmanis, V.O. and G.R. Edwards. 1974. Promotion of flower initiation in apple trees by short exposure to the ammonium ion. *Austral. J. Plant Physiol.* 1:99-105.
- Grasmanis, V.O. and G.W. Leeper. 1967. Ammonium nutrition and flowering of apple trees. *Austral. J. Biol. Sci.* 20:761-767.
- Leonard, C.D., I. Stewart, and I.W. Wander. 1961. A comparison of ten nitrogen sources for 'Valencia' oranges. *Florida State Hort. Soc.* 74:79-86.
- Lovatt, C.J., Y. Zheng, and K.D. Hake. 1988a. Demonstration of a change

- in nitrogen metabolism influencing flower initiation in Citrus. *Israel J. Bot.* 37:181-188.
- Lovatt, C.J., Y. Zheng, and K.D. Hake. 1988b. A new look at the Kraus-Krabill hypothesis and flowering of Citrus. *Proc. 6th Intl. Citrus Congr.* 1:475-483.
- Lovatt, C. J., O. Sagee, and A.G. Ali. 1992. Ammonia and/or its metabolites influence flowering, fruit set, and yield of the 'Washington' navel orange. *Proc. Intl. Soc. Citricult.* 1:412-416.
- Monselesse, S.P. 1985. Citrus and related genera, p. 257-294. In: A.H. Halevy (ed.). *CRC handbook of flowering.* vol. 2. CRC Press, Boca Raton, Fla.
- Reuther, W. 1973. Climate and citrus behavior, p. 280-337. In: W. Reuther (ed.). *The citrus industry.* vol. 3. Univ. of California, Div. of Agr. Sci., Berkeley.
- Reuther, W. and D. Rios-Castano. 1969. Comparison of growth, maturation and composition of citrus fruits in subtropical California and tropical Columbia. *Proc. 1st Intl. Citrus Symp.* 1:227-300.
- Sagee, O. and C.J. Lovatt. 1991. Putrescine concentration parallels ammonia and arginine metabolism in developing flowers of 'Washington' navel orange. *J. Amer. Soc. Hort. Sci.* 116:280-285.
- SAS Institute. 1988. SAS/STAT users's guide. release 6.03. SAS Institute, Cary, N.C.
- Sharples, G.C. and R.H. Hilgeman. 1969. Influence of differential nitrogen fertilization on production, trunk growth, fruit size and quality and foliage composition of 'Valencia' orange trees in central Arizona. *Proc. 1st. Intl. Citrus Symp.* 3:1569-1578.
- Singh, H.P. and K.L. Chadha. 1988. Regulation of flushing and flowering in acid lime (*Citrus aurantifolia* Swing.). *Progr. Hort.* 20:1-6.
- Southwick, S.M. and T.L. Davenport. 1986. Characterization of water stress and low temperature effects on flower induction in citrus. *Plant Physiol.* 81:26-29.
- Southwick, S.M. and T.L. Davenport. 1987. Modification of water-stress induced floral response in 'Tahiti' lime. *J. Amer. Soc. Hort. Sci.* 112:231-236.