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The effect of timing of post-harvest foliar urea sprays on nitrogen absorption and partitioning in peach and nectarine trees

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SUMMARY

The effects of timing of autumn foliar urea-N sprays on nitrogen absorption and partitioning were studied in mature peach and nectarine trees. A 10% ^{15}N enriched urea solution was applied by either dipping individual shoots in 1995 or spraying whole tree canopies in 1996. Trees whose canopies were sprayed during the post-harvest period with a 10% w:v urea solution in 1996 were excavated in the dormant season, and ^{15}N contents and distribution were determined. Peach leaves rapidly absorbed urea-N irrespective of application date, and transport of urea-N to perennial tree parts occurred primarily within 4–7 d after application. Between 48 and 58% of the urea-N applied was recovered in abscinded leaves and perennial organs. Leaves exported ⩾60% of the foliar-applied urea-N following application in early autumn (September or October), but <50% export occurred when applied shortly before leaf fall (November). Of the urea-N translocated, most was recovered in roots (⩾38%) following application in September or October. Urea-N applied in November, however, remained largely in the current year wood (ca. 45%). Thus, export and translocation of foliar applied urea-N diminished during the final stages of leaf senescence. Foliar application of urea in September or October supplied the equivalent of about 20% of crop nitrogen content, but only 14% (i.e. ca. 30% lower) when applied shortly before leaf senescence in November.

Nectarine and peach leaves rapidly absorb foliar-applied urea (Rosecrance *et al.*, 1998). Nitrogen uptake through leaf surfaces may permit the reduction of soil N application in orchards, thus decreasing the potential for nitrate leaching to the groundwater. Fertilization in late summer and early fall is recommended to reduce excessive peach shoot growth and increase N storage prior to winter dormancy (Johnson and Uriu, 1987). However, soil application in winter may increase the probability of nitrate leaching to groundwater during the winter months when the N uptake capacity of many orchard species is limited (Weinbaum *et al.*, 1978).

Recovery of soil-applied N by fruit trees typically ranges between 25–35% (Khemira, 1995), while N recovery is typically >60% following foliar N application (Hill–Cottingham and Lloyd-Jones, 1975; Shim *et al.*, 1972; Weinbaum, 1988). Shim *et al.*, (1972) concluded that the N utilization efficiency (N recovered/N applied to the tree) of foliar urea sprays was four-fold greater than soil N applications. Moreover, during the post-harvest period, high concentrations of foliar urea can be applied because leaf senescence has begun, and the physiological consequences of urea-induced phytotoxicity are minimal.

In previous studies, where foliar applications of urea were applied in spring, only low urea concentrations could be applied to minimize phytotoxicity. This applied foliar urea satisfied only a small proportion of tree N demand (Weinbaum, 1988 and references therein).

During the autumn, leaves senesce and export part of their nitrogen through the phloem to the trunk and root system (Shim *et al.*, 1972). Foliar urea applications to fruit trees at this time have increased N storage and stimulated shoot growth during the following season (Han *et al.*, 1989; Shim *et al.*, 1972), but also have accelerated leaf abscission particularly when high rates were used (Terblanche *et al.*, 1970). Thus, foliar application of urea during the autumn should be timed to maximize urea-N resorption and minimize premature leaf abscission. Therefore, we conducted two experiments to evaluate the effectiveness (i.e. absorption and translocation) of post-harvest foliar N applications to peach and nectarine trees at different times during the autumn. We hypothesized that application of foliar N late in the season, i.e., about the time of natural leaf senescence, would reduce N absorption and export compared with applications made earlier in the season. The objectives of the study were: 1) to quantify leaf absorption and export of foliar-applied urea-^{15}N at different times during the autumn, and 2) to characterize the distribution of ^{15}N in perennial storage organs following ^{15}N-urea application.

MATERIALS AND METHODS

Experiment 1

The experiment was conducted in the autumn of 1995 on six, seven year old 'Fantasia' nectarine trees on 'Nemaguard' rootstock located at the UC Davis experimental farm. Trees were spaced 1.8 m apart within the row and 6 m between rows, and the orchard received commercial management regarding fertilization, pruning, irrigation, weed and pest control, and thinning of fruits. Experimental trees averaged 3.1% leaf N concentrations in July, which is above the leaf N sufficiency range of 2.6 to 3.0% N for peach and nectarine in California (Johnson and Uriu, 1989). A regression equation was developed to assess the relationship between nectarine leaf size and the amount of urea retained in September 1995 (following Klein and Weinbaum, 1985). Leaf areas of 70 leaves of various sizes taken from the outer canopy of the trees were determined. These leaves were then weighed, dipped in a 10% urea solution made up with 0.1% Triton X-100, shaken gently to remove excess solution, and reweighed. The urea leaf retention equation was: $y = 0.00367x$, $r^2 = 0.87$, where x is leaf area (mm^2) and y is the amount of urea applied (mg). Preliminary studies confirmed the accuracy of this volume-retention equation by indicating a close agreement between the amount of urea recovered from the leaves immediately after application and the amounts retained on the leaf surfaces as calculated from the regression equation (data not shown). In this paper, we use the term "N applied" to refer to the amount of urea-N initially retained on the leaf surfaces.

The kinetics of foliar urea uptake from the nectarine leaves were determined on 2 October and 15 November 1995. Five leaves from each of six shoots per tree (30 leaves per tree) were dipped for 5–7 seconds in a 10% (w:v) ^{15}N-enriched urea (4.62 atom % excess) solution made up with 0.1% Triton X-100. Six replicate trees were treated, and leaves were sampled at 0, 8, 24, 48, 96 and 336 h after urea application. Slight leaf tip necrosis occurred within 96 h of treatment.

At each sampling time, one shoot (five leaves) per replicate was removed and shaken for 2–3 min in 20 ml of water to wash off and recover residual urea remaining on leaf surfaces. After rinsing the leaves, leaf areas were determined using a Delta T leaf area meter (Decagon, Pullman, WA). The urea washed off leaf surfaces was analysed colorimetrically by the modified diacetyl method (LeMar and Bootzin, 1957; Polacco, 1976). Leaves were then dried at 60°C, pulverized to a fine powder in a ball mill, and sent to Isotope Services, Los Alamos, N.M. for ^{15}N analyses. Recovery of foliar-applied ^{15}N was calculated using the following equation (Hauck and Bremner, 1976);

$$\text{Recovery } ^{15}\text{N } (\%) = \frac{100p(c - b)}{f(a)}$$

where p = the leaf N content, f = the N applied to the leaf (g N $leaf^{-1}$), a = the atom % excess of ^{15}N in fertilizer, b = the atom % ^{15}N of the unlabelled leaf fraction, and c = the atom % ^{15}N of the labelled leaf fraction.

Leaves were sampled weekly between 1 October and 1 December on six control trees. Leaf areas and N concentrations were determined (Carlson, 1978) to assess the natural patterns of leaf N resorption. Eight mesh bags were also used to enclose branches of these trees on 1 November. Abscinded leaves were collected weekly from these bags to estimate the patterns of natural leaf fall. The leaves enclosed in the mesh bags represented about 20% of the total leaf area of the trees (data not shown). Leaf samples were dried, weighed, and the leaf fall percentages calculated on the basis of total leaf dry weight in the mesh bags.

The experimental design was completely randomized, with six replicates per harvest interval. Differences between ^{15}N and total N recoveries were assessed by Student's T test. Percentage data were arcsin transformed before analysis. A probability of <5% was considered significant.

Experiment 2

Sixteen, eight year old peach trees (*Prunus persica*, (L.) Batsch) cv. O'Henry on 'Lovell' rootstocks were selected from the Wolfskill Experimental Orchard in Winters, CA. Tree selection was based on similarities in July leaf N concentrations, and trunk cross-sectional areas. Trees were spaced 2 m apart within the row and 5.5 m between rows (969 trees ha^{-1}), and their canopies trained to the "KAV-V" (DeJong *et al.*, 1994). The soil is classified as a Yolo clay loam (Fine, mixed, non-acid, thermic Mollic Xerfluvent). Trees were irrigated weekly by micro-jet sprinklers and fertilized during the spring with 112 kg N ha^{-1}. July leaf N concentration averaged 2.7% in the selected trees.

Four trees were sprayed on 20 September, 11 October and 1 November 1996 with an urea solution (10%, w:v) enriched with 4.623 atom % ^{15}N excess and 0.1% Triton X-100. Four trees were left unsprayed as controls. A mechanical cherry picking machine (tree squirrel) allowed easy access to the whole tree canopy and facilitated complete canopy coverage. A tarpaulin was placed underneath the trees to collect the urea solution that dripped from the trees. Urea collected on the tarpaulin was then removed from the orchard. A volume-retention equation for the peach trees was developed following the same procedures as used in the previous experiment, except that the equation was based on leaves that were sprayed with the urea solution, rather than dipped into the solution. The urea leaf retention equation for Expt. 2 was: $y = 0.00273x$, $r^2 = 0.86$. Again, there was close agreement between amount of urea retained on the leaf surfaces immediately after urea application and the retention equation determined earlier (data not shown). This equation was used to quantify the amount of urea-N intercepted by the canopy of each tree. Abscinded leaves were collected from underneath the trees weekly, weighed, and subsamples were taken to measure leaf areas and wet-to-dry weight ratios. This allowed the calculation of the total leaf areas per tree and weights of abscinded leaves of the treated trees.

The kinetics of foliar urea uptake were determined from samples of ten leaves taken at 8, 2, 48 and 168 h after urea application, as well as from abscinded leaves. Eight mesh bags were used to enclose branches around the periphery of each tree soon after urea application to collect the abscinded leaves. The samples were processed and analysed as described in Expt. 1.

On 14 January 1997, the 12 trees that had previously received foliar-applied urea were excavated with a backhoe and separated into the following five fractions: roots, rootstump, trunk, canopy branches, and current year wood. The various tree factions were weighed with a load cell and chipped mechanically. About 3 kg subsamples were weighed fresh, dried at 60°C, reweighed, and processed similarly to the leaf samples. The ^{15}N enrichment in treated trees was calculated by subtracting the natural ^{15}N abundance of untreated control trees (0.3775 atom % ^{15}N). Foliar N absorption was calculated as the amount of labelled ^{15}N found in the harvested trees, plus that recovered in the abscinded leaves. Note: it was assumed that all ^{15}N found in abscinded leaves was absorbed, since almost no ^{15}N remained on leaf surfaces 300 h after application (Rosecrance *et al.*, 1998). The amount of N derived from applied urea and present in each organ was calculated by multiplying the amount of ^{15}N excess in the tissues by 21.6 (the ratio between the 100% total N to the 4.623% 15N excess of the enriched urea).

The experiment was set up as a completely randomized design, with three applications times and a control with four replicates. The effects of urea-N application time on foliar N uptake and export were assessed by a one-way analysis of variance and mean separation by Duncan's multiple range test ($P = 0.05$).

RESULTS

Pattern on leaf abscission and N remobilization during leaf senescence

The time course of leaf abscission and leaf N contents are presented in Figure 1. Leaf abscission occurred primarily between late October and mid-November in

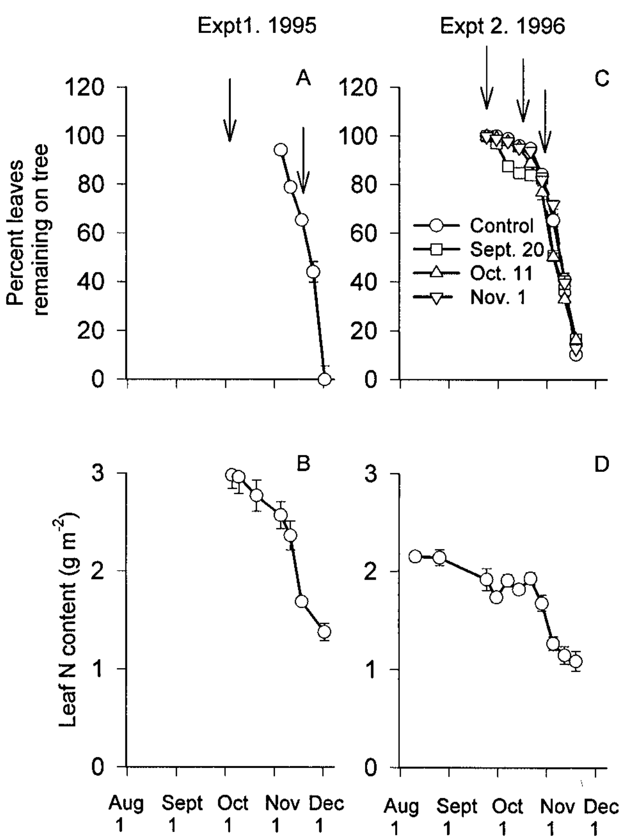

FIG. 1
Seasonal patterns of leaf fall in 1995 (A), and 1996 (C), and leaf N per unit leaf area in 1995 (B) and 1996 (D). The arrows indicate times of foliar urea applications on 2 October and 15 November 1995, and 20 September, 11 October, and 1 November 1996. The vertical bars indicate ± SE; n = 4.

both 1995 and 1996 (Figures 1A and C). The urea application in September caused <20% of the leaves to abscind early (Figure 1C), and most of these leaves were located in the tree interior (personal observation). Nitrogen remobilization from exterior canopy leaves also occurred primarily between late October and mid-November, just prior to leaf abscission in control trees (compare Figures 1A and B, and 1C and D). Nectarine and peach trees remobilized 54 and 45% of their leaf N, respectively, and most of this occurred between late October and mid-November (calculated from Figures 1B and D). The urea applications in November of 1995 and 1996 occurred as leaves were beginning to abscind and leaf nitrogen was being remobilized.

Kinetics of foliar-applied ^{15}N-urea uptake

The patterns of urea-^{15}N recovery in 1995 and 1996 are presented in Figure 2. Less than 20% of the foliar-applied ^{15}N-urea was recoverable in the leaf rinsate 48 h after spraying in Expt. 1, and less than 35% in Expt. 2. The recovery of urea in the wash solution was not influenced by application time in either experiment (Figures 2A and C). Concomitant with urea disappearance from the leaf surfaces, the percentage recovery of ^{15}N in leaves increased, peaked 48 h after urea application, and then declined (Figures 2B and D). Leaf ^{15}N declined between 4 and 7 d following applications (Figures 2B and D). Foliar ^{15}N-urea application in November resulted in significantly greater ^{15}N retention in the abscinded leaves compared with the earlier application dates in Expt. 1, and followed the same trend in Expt. 2. In November 1995, for example, ^{15}N translocation from leaves lasted only 1 d and was of small intensity, thus indicating low withdrawal compared with the October application (Figure 2B). Similar trends occurred in Expt. 2 in 1996, although the differences between the November and October values were less pronounced.

Foliar uptake and recovery of urea-N in whole, mature trees

Between 48 and 58% of the urea applied to the tree canopies was recovered either in abscinded leaves or in perennial tree parts (Table I). The date of urea application did not affect the percentage recovery of urea-N, but did change the partitioning of urea-N. Significantly more urea-N was recovered in perennial tree parts and less in the abscinded leaves following application in September or October compared with application in November. Perennial tree parts contained 60, 64, and 48% of the total urea-N absorbed after the September, October and November treatments, respectively.

As tree dry weights and N contents did not vary with the date of foliar application, the data were combined (Table II). The canopy branches and roots (including rootstump) comprised 47 and 32% of the total tree dry weight and 27 and 46% of the total tree nitrogen, respectively. Thus, roots were the major organ for N accumulation in mature peach trees. Most foliar-absorbed N was also recovered in the roots following application of ^{15}N-enriched urea in September or October, containing 38 and 45% of the total ^{15}N

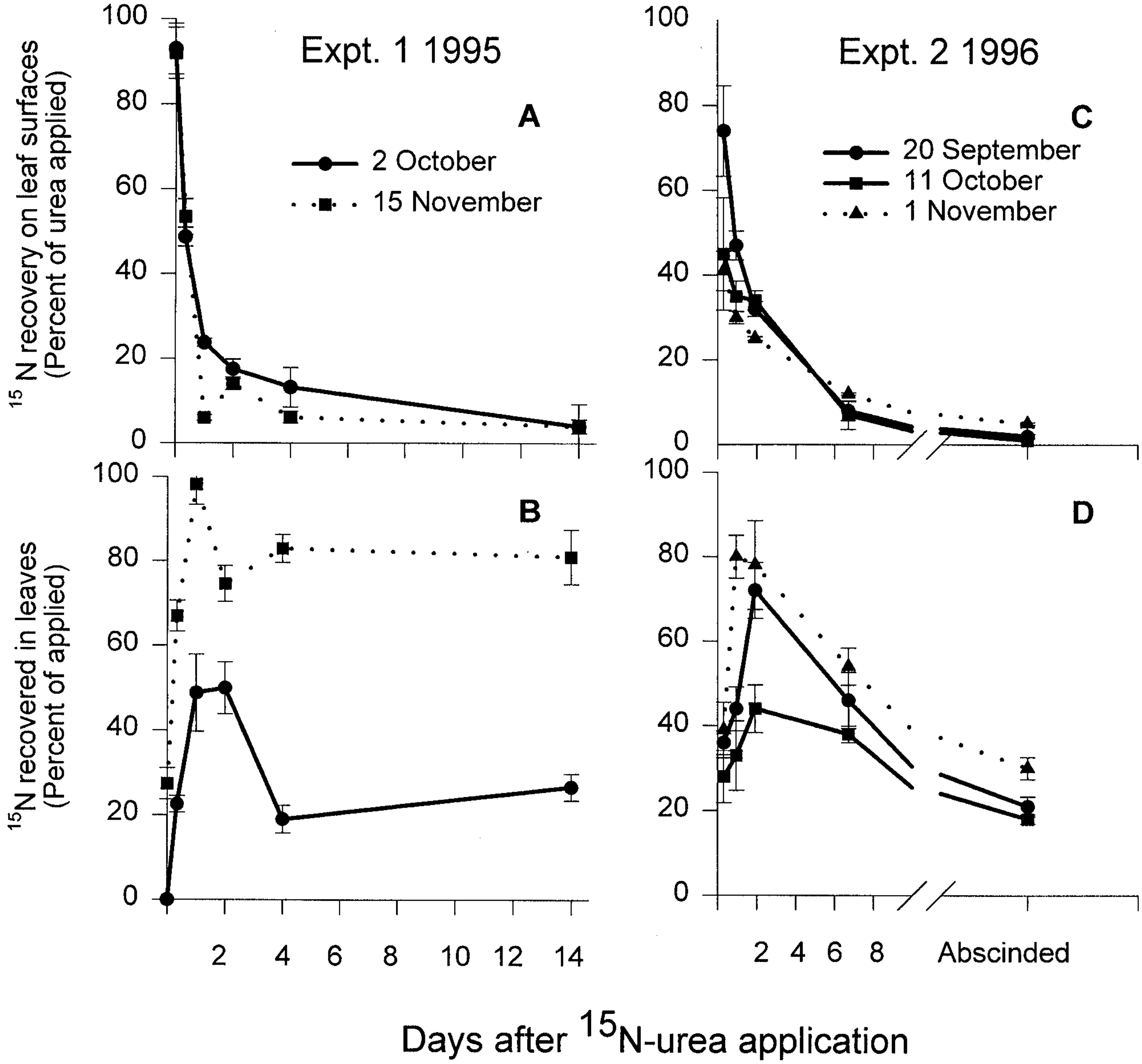

FIG. 2
Kinetics of urea disappearance from leaf surfaces in 1995 (A) and 1996 (C), and ^{15}N recovery in 1995 (B) and 1996 (D) following foliar application of labeled urea. Leaves were sampled 0, 8, 24, 48, 96, and 336 h after foliage was dipped in a 10% ^{15}N-urea solution in 1995 (Expt. 1), and sampled 8, 24, 48, and 168 h after the spray application, as well as, from abscinded leaves in 1996 (Expt. 2). The vertical bars indicate ± SE; n = 6 in Expt. 1 and n = 4 in Expt. 2.

recovered in perennial tissues, respectively. The November application resulted in only 28% recovery of ^{15}N-urea in roots. As a result, roots contained almost double the amount of ^{15}N when applied in September or October compared with November.

DISCUSSION

Nectarine and peach leaves absorbed foliar-applied urea rapidly, irrespective of application date, and was similar to that reported for many other fruit tree species (Swietlik and Faust, 1984). The translocation of urea-N

TABLE I
Amounts of foliar urea-N (g N tree^{-1}) applied onto the "O'Henry" tree canopy, recovered in perennial tree tissues, and removed in the abscised leaves. Each value is a mean of four replicates; mean separation was conducted by Duncan's multiple range test

	Foliar urea N (g N tree^{-1})			
Date of urea application	A Applied to leaf canopy	B Recovered in perennial tree parts	C Removed in abscinded leaves	D Percentage recovery $(\frac{B+C}{A})\times 100$
20 September	35.2	10.7 a	7.4 ab	51.3
11 October	32.1	10.0 a	5.6 b	48.4
1 November	28.1	7.9 b	8.5 a	58.4
P value	n.s.	0.007	0.014	n.s.

TABLE II
'O'Henry' peach tree dry weight[1] (kg tree^{-1}), N content[1] (g tree^{-1}), and the effect of urea application date on the distribution of ^{15}N (mg tree^{-1}) in different organs in January. Numbers in parentheses are percentages of the total in perennial tissues. Values are the mean of 12 replicates for dry weight and N content and four replicates for Urea-N content. Mean separation among application dates was conducted using Duncan's multiple range test

	Tree part						
	Roots[2]	Root-stump	Trunk	Canopy branches	Current year wood	Total in perennial tissues	Abscinded leaves
Dry weight (kg tree^{-1})	4.3	4.3	2.5	12.8	3.1	27	2.4
	(16)	(16)	(9)	(47)	(11)		
N content (g tree^{-1})	31	16	5	28	22	102	50
	(30)	(16)	(5)	(27)	(22)		
Urea-N (g tree^{-1})							
9 September	3.0 a	1.1 a	0.39	2.3	3.9 a	10.7 a	7.4 ab
	(28)	(10)	(4)	(22)	(36)		
11 October	3.1 a	1.4 a	0.28	2.4	2.8 b	10.0 a	5.6 b
	(31)	(14)	(3)	(24)	(28)		
1 November	1.5 b	0.73 b	0.26	1.8	3.6 ab	7.9 b	8.5 a
	(19)	(9)	(3)	(23)	(46)		
P value	0.001	0.023	n.s.	n.s.	0.029	0.007	0.014

[1]Tree dry weights and total N contents did not vary with the foliar urea application date, so the data were combined.
[2]Lateral roots that emanated from the rootstump.

out of the leaves was also rapid, with much of it occurring within 4–7 d of application (Figures 2B and D). Our data are consistent with those of Dilley and Walker (1961) who found that urea was readily hydrolyzed and assimilated into amino acids within 20 h of delivery to the leaves through the petiole. A number of previous studies, however, reported that foliar urea applications to peach leaves were ineffective (El-Banna *et al.*, 1981; Norton and Childers, 1954; Proebsting, 1951; Weinberger *et al.*, 1949). The resolution obtainable in these studies, however, may have been compromised by the application of solutions containing low urea concentrations (<1.5%) and delayed leaf sampling after urea application (>5 d). Rapid urea absorption and export of urea-N out of peach leaves probably misled researchers into thinking that foliar urea-N was not absorbed by peach leaves.

Foliar-applied urea-N was translocated primarily to roots following application in September or October (Table II). The export of foliar-applied urea-N out of young shoots and into roots is important in peach orchards because trees are often heavily pruned, removing substantial quantities of current year wood. In contrast, a number of studies using different species have reported that foliar-applied urea-N remained primarily in the twigs subtending the sprayed leaves and little was translocated to roots (Forshey, 1964; Klein and Weinbaum, 1984). These experiments, however, were conducted during the spring, and the export of urea-N to other organs may differ depending on the sink activity at the time of application. During the spring, foliar-applied urea-N accumulates primarily in the developing inflorescences and fruits (Gooding and Davies, 1992; Klein and Weinbaum, 1984). During leaf senescence, shoot growth is minimal and soil-applied nitrogen (Munoz *et al.*, 1993) as well as foliar N (Table II) accumulates in peach roots. Thus, the range of application dates may explain the conflicting reports in the literature concerning the abilities of trees to translocate foliar-applied urea-N.

Nitrogen movement out of the leaf was restricted when urea was applied in November, especially the mid-November date of Expt. 1 (Figure 2B). In November, leaves were yellowing and in a more advanced stage of senescence than in September or October. As leaves senesce, membranes break down, enzymes are catabolized, and vascular connections are broken (Feller and Fischer, 1994). These processes probably reduce N export from leaves. Therefore, to maximize N utilization by the peach tree, foliar urea sprays need to be applied before leaf senescence and while N remobilization processes are still under way. It appears not to matter if the application is made well ahead of leaf senescence since the September and October treatments in Expt. 2 did not differ substantially in N partitioning (Tables I and II). However, there are large differences in ^{15}N recovery measured 2 d after treatment (Figure 2D). The 11 October application occurred just prior to the rapid remobilization of N out of leaves (Figure 1D). Ammonium assimilating enzymes such as glutamine synthetase may increase just prior to leaf senescence (Streit and Feller, 1983), which may have increased the rate of ^{15}N-urea export out of the leaves at this time.

Peach trees absorbed between 48 and 58% of the urea-N intercepted by the canopy (Table I). Similar percentages have been reported in young, potted nectarines trees following foliar urea application (Tagliavini *et al.*, in press) and in wheat (Gooding and Davies, 1992), but are substantially lower than the 80% absorption reported in apples (Shim *et al.*, 1972) and the 99% absorption in tomatoes (Nicoulaud and Bloom, 1996). These studies in apple and tomato, however, may have overestimated urea absorption because they based their absorption values on urea disappearance from leaf surfaces and did not account for possible losses of urea from the leaves. In the present study, urea absorption estimated from urea disappearance from leaf surfaces approached 100% (Figures 2A and C), substantially higher than that actually recovered in the tree. Some of the possible avenues for foliar urea-N loss include ammonia volatilization from leaf surfaces (Bowman and Paul, 1990; Smith *et al.*, 1991), urea being washed off leaf surfaces by rain or dew (no rainfall occurred during the first week after application in these experiments, but dew was common), and exudation of N from roots (Zhang *et al.*, 1991). More research will be needed to quantify these potential losses.

Still, the foliar urea-N recovery percentages found in this study were about double those of soil-applied N in fruit trees (Khemira, 1995). The percentage recovery of applied N following foliar vs. soil application, however, must be evaluated in terms of the capacity to meet plant demand. In California, crop N removal in 'O'Henry' peaches is about 47 g nitrogen per tree (Weinbaum *et al.*, 1992). A single foliar application of urea-N (10%) in September and October supplied 9.2 to 10.0 g N tree^{-1}, equivalent to about 20% of the nitrogen removed in the crop. This percentage is significantly higher than that reported in prune (Weinbaum, 1988) primarily because a high concentration of foliar urea was used. Therefore, it appears feasible that a substantial component of peach and nectarine N demand could be met with one to several post-harvest foliar urea applications. It remains to be seen, however, whether tree response to foliar-applied N is similar to that of soil-applied N. Soil N may be needed to stimulate root growth and cytokinin production. Further research will be needed to determine if foliar urea can maintain normal root growth and fruit productivity of peach and nectarine trees.

In summary, we found that: 1) peach leaves absorbed a considerable fraction of the foliar urea applied between September and November; 2) foliar-absorbed N was translocated rapidly to perennial tree parts (primarily within 4–7 days after application), and much of it accumulated in roots; 3) export of urea-N from leaves and transport of urea-N to roots were reduced when foliar application of urea was delayed to the onset of leaf senescence in November; and 4) a single foliar application of urea-N (10%) before leaf senescence was able to supply about 20% of the crop N content.

These results suggest that a well-timed foliar urea application in the autumn could efficiently supplement soil-applied fertilizer N, and thus, reduce the potential for nitrate leaching to the groundwater. Additional research is needed to test the feasibility of incorporating foliar applications of urea into the orchard fertilization program. It would be useful to have information on the effects of both high foliar urea concentrations and repeated applications on peach and nectarine vegetative growth and productivity.

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