Foliar- and Fruit-applied Strontium as a Tracer for Calcium Transport in Apple Trees

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Abstract. Application of calcium (Ca) sprays is a recommended practice to reduce the incidence of Ca-related disorders such as bitter pit in apple (*Malus × domestica*), but effectiveness of sprays to increase Ca concentrations in the fruit is not always consistent. Strontium (Sr) has been used as a Ca analog to evaluate Ca transport processes and distribution in plants. A field study was conducted using foliar- and fruit-applied Sr as a tracer for Ca transport in 20-year-old ‘Honeycrisp’ apple trees on Malling.26 (M.26) rootstock. The objectives of this study were to 1) measure the amount of Sr translocation from leaves to fruit, 2) determine the effectiveness of eight sprays applied over the growing season vs. four late-season sprays on increasing Sr concentrations in leaves and fruit, and 3) evaluate the effect of an experimental adjuvant consisting of alkyl-polysaccharides and monosaccharides on spray efficacy. Seven treatments were tested, which included a control and six Sr treatments applied in various combinations with or without an adjuvant. Trees were sprayed four or eight times during the growing season, either directly to leaves and fruit or to leaves only (fruit covered during application). Spray treatments did not significantly affect total fruit fresh or dry weight. Although some discrimination between Ca and Sr was detected, the similar distribution of Ca and Sr in fruit tissue of control treatments suggested that Sr is a suitable tracer for Ca. Based on the covered vs. uncovered fruit treatments, about 11% to 17% of the Sr in the fruit came from Sr applied directly to the leaves. Eight spray applications over the growing season more than doubled both the concentration and content of fruit Sr compared with four late season sprays. The tested adjuvant doubled Sr absorption by and translocation to fruit compared with not using an adjuvant. Assuming similar transport for Ca and Sr, and adjusting for the atomic weight of Ca relative to Sr, the maximum increase in fruit Ca concentration at harvest from foliar and fruit applications (eight sprays with adjuvant and uncovered fruit) would have been as follows: core = 78 mg·kg⁻¹; flesh = 35 mg·kg⁻¹; peel = 195 mg·kg⁻¹; entire fruit = 67 mg·kg⁻¹. In addition to being an underused tool for studying Ca transport patterns, the results also suggest that use of Sr may be a novel technique for testing the efficacy of various adjuvants used to enhance uptake and transport of Ca in leaves and fruit.

Quality and storability of apple fruit are often strongly associated with levels of Ca in fruit (Vang-Petersen, 1980). Of the Ca-related quality problems in apples, bitter pit is one that is particularly challenging to control in certain cultivars. While bitter pit can be controlled to some degree by ensuring an even crop load and maintaining uniform soil moisture, application of Ca sprays through the growing season is often a general recommendation to minimize incidence of the disorder (Ferguson and Watkins, 1989).

Evaluating the effects of foliar and fruit Ca applications is often problematic, because it is difficult to determine the extent of Ca absorption in tissue from the sprays. Without any Ca treatment, apple fruit Ca concentrations can vary by as much as 2- to 3-fold within the same tree (Perring and Jackson, 1975). Only small amounts (about 1 to 2 mg Ca per fruit) are needed to improve storage quality (Wilkinson,

1968). However, relatively large amounts of Ca are already present in the tissue (about 7 to 11 mg Ca per fruit) and its concentration and content can be affected by crop load, fruit size, weather, and other factors (Ferguson and Watkins, 1992; Perring and Jackson, 1975). Increasing the number of replications and number of fruit sampled would be methods of dealing with the high variability of fruit Ca, but these approaches also increase labor and analytical costs. Using ⁴⁵Ca would be another method to evaluate effectiveness of foliar sprays, but cost and permitting concerns make a field study using radioactive Ca impractical. Van Goor (1973) used fruit-applied ⁴⁵Ca in a lab and pot study to show the extent of Ca penetration through the peel.

Strontium (Sr) is an element with chemical properties that are similar to those of Ca, yet is found naturally in much lower amounts in soil and plant tissue. While radioactive Sr (⁹⁰Sr) is a major health concern, stable Sr (atomic weight of 88) at low to moderate concentrations is considered relatively nontoxic to plants and animals (ATSDR, 2004; Kabata-Pendias and Pendias, 2001). Because of their similarities, use of Sr as a tracer for Ca has been reported in

plant studies to understand Ca transport patterns (Laszlo, 1994). Plant uptake, transport, and distribution of Ca and Sr have been shown to be similar, although Sr was not able to completely substitute for Ca in metabolic or physiological processes (Hutchin and Vaughan, 1968; Queen et al., 1963).

Studies to simulate radioactive fallout have been conducted to determine the extent of Sr translocation to and absorption by fruit following foliar application with ⁸⁵Sr (Bengtsson, 1992; Carini and Bengtsson, 2001; Carini et al., 2003). In general, translocation of ⁸⁵Sr to fruit following application was found to be minimal or nonexistent. In studies with apples, almost all radioactivity was restricted to the peel tissue and was attributed to direct application to the fruit (Bengtsson, 1992).

Wills et al. (1975) reported that Sr salts applied to apple fruit reduced the incidence of internal breakdown and bitter pit compared with those not treated, but that Sr applications were no more effective than Ca applications. Conway and Sams (1987) found that Ca was more effective than Sr in reducing fruit decay caused by *Penicillium expansum* when results were expressed on a weight basis of element applied. When expressed on a molar basis, however, the effect of the two cations on fruit decay was similar. Siddiqui and Bangerth (1995) reported no differences in fruit firmness at harvest following foliar applications of Ca and Sr, but after 20 d in storage fruit from Ca-treated branches were firmer and higher in pectins than those from Sr-treated branches.

While the effects of Sr on apple fruit firmness and bitter pit have been evaluated, the use of Sr as a tracer for foliar and fruit applications of Ca has not. Therefore, this study used foliar- and fruit-applied Sr as a tracer for Ca transport with the following objectives: 1) measure the amount of Sr translocation from leaves to fruit, 2) determine the effectiveness of eight sprays applied over the growing season vs. four late season sprays on increasing Sr concentrations in leaves and fruit, and 3) evaluate the effect of an experimental adjuvant on spray efficacy. ‘Honeycrisp’ was chosen as the test cultivar for this study because of its susceptibility to bitter pit (Rosenberger et al., 2004).

Materials and Methods

This research was conducted in 2003 at the University of Minnesota, Horticultural Research Center in Chanhassen, on a single row of 20-year-old ‘Honeycrisp’ trees on M.26 rootstock spaced 3.1 m apart within rows. Trees were grown on a Hayden loam soil (Fine-loamy, mixed, superactive, mesic Glossic Hapludalfs) with the following chemical properties (0 to 25 cm): pH (1 soil : 1 water) = 6.3; organic matter = 3.5%; Bray 1 P = 11 mg·kg⁻¹; 1 N ammonium acetate extractable K, Mg, Ca, and Sr = 147, 352, 2202, and 4.5 mg·kg⁻¹, respectively (Brown, 1998). The nearly 500-fold higher availability of soil Ca compared with Sr on a weight basis (>1000-fold higher availability on an atom basis) suggests that foliar-applied Sr could be a suitable tracer for Ca, assuming that transport properties in the plant are similar.

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The following seven treatments were tested:

- 1) Control (no Sr applied).
 - Sprays applied over the growing season on eight occasions.
 - 2) Sr without adjuvant, fruit covered during spray application.
 - 3) Sr without adjuvant, fruit uncovered during spray application.
 - 4) Sr + adjuvant, fruit covered during spray application.
 - 5) Sr + adjuvant, fruit uncovered during spray application.
- Late-season sprays applied on four occasions.
- 6) Sr + adjuvant, fruit covered during spray application.
 - Sr + adjuvant, fruit uncovered during spray application.

A row of 14 trees planted in a north to south direction was divided so that there were two blocks on the east side of the trees and two blocks on the west side, allowing each treatment to be replicated four times in a randomized complete block design. A block consisted of seven half trees and each half tree was considered a plot. A treatment was assigned on the east side of the tree as part of one block and a treatment was assigned on its west side as part of another block. Each treatment within a block was applied to a single branch. Branch sections of 1 to 2 m in length with at least 10 to 12 blossom clusters were selected and tagged at the beginning of the study.

Strontium spray solutions were mixed using $\text{Sr}(\text{NO}_3)_2$ as the Sr source (Fisher Scientific, Pittsburgh, Pa.). The nitrate source was selected because many popular Ca products available in the midwestern U.S. use $\text{Ca}(\text{NO}_3)_2$ as the primary source of Ca. The concentration of $\text{Sr}(\text{NO}_3)_2$ applied was 35 mM (3080 mg·L⁻¹ Sr). This was based on concentrations of Ca (1400 mg·L⁻¹) recommended to control bitter pit. Because the atomic weight of Sr is about 2.2 times greater than Ca, the Sr applied was equivalent to Ca on an atom basis rather than an equivalent weight basis.

The adjuvant tested was an experimental product (Agrilance LLC, St. Paul, Minn.) and mixed at 1% by volume in those treatments that included an adjuvant. Alkyl-polysaccharides as a surfactant and additional monosaccharides were the primary components of the adjuvant. Spray applications over the growing season were made eight times at about 10- to 14-d intervals, beginning 14 d after petal fall. The late-season spray schedule included only the last four dates of the eight-spray application schedule. Spray application dates were 10 June, 19 June, 3 July, 15 July, 28 July, 12 Aug., 26 Aug., and 9 Sept.

The entire length of the branch section comprising a plot (main branch + all side branches) was sprayed to runoff with a hand-held spray bottle. For the covered fruit treatment, fruit were enclosed in Whirl-Pak (Nasco, Fort Atkinson, Wisc.) plastic bags immediately before application. The bags were removed as soon as the spray residue on bag surfaces was dry, usually within 1 h after application.

Leaf samples (10 leaves per plot) and fruit

samples (up to 5 fruit per plot) were collected for nutrient analysis on 22 July, which was after the first four spray applications and before the last four late-season spray applications. Therefore, Sr applications for treatments 6 and 7 (late season sprays) had not yet been applied at this first sampling date and they had been treated the same as the control. Fruit and leaf samples were collected again from the same branch after fruit were mature on 23 Sept. (fruit) and 1 Oct. (leaf). Due to uneven fruit drop it was not possible to sample 5 fruit from every plot on both dates, so smaller samples were collected from some plots on the July sampling date to leave the maximum number of fruit for the September sampling of mature fruit. The average crop load on the sprayed branches before the July harvest date was 7 to 8 apples per branch (about 1.5 m in length). Within 2 h of sampling, both leaf and fruit samples were soaked in a dilute (1 soap : 60 water) soap solution (VersaClean Detergent, Fisher Scientific) for 30 s and then rinsed three times in deionized water. The number of apples per plot was counted. Fruit were subdivided using an apple peeler and a knife into peel, flesh, and core samples for analysis. Fresh weight of each fruit part was recorded. Both leaves and fruit parts were dried at 60 °C until a constant weight was achieved and then the dry weight of each fruit part was recorded. Dried samples were ground with a Wiley mill for leaf, core, and peel tissue and a Stein mill for flesh tissue. Samples were dry-ashed and Sr and Ca were determined using an inductively coupled plasma optical emission spectrometer (model 3560; Applied Research Laboratories, Sunland, Calif.) following the procedures of Munter et al. (1984). Data for Sr and Ca in all fruit tissue are expressed on both a con-

centration basis (mg·kg⁻¹) and content basis (µg or mg per fruit tissue). The sum of Sr and Ca in the fruit parts, taking into account dry weight differences, was used to calculate the concentration and content of these elements in the whole fruit.

Data were analyzed as a randomized complete block design with a split-plot in time treatment arrangement using the Proc Mixed program in SAS (SAS Institute, 1999). Because of the large differences in Sr concentrations among treatments, all Sr data were log transformed before statistical analysis to determine significance (Steele and Torrie, 1980). Non-transformed means are presented in the tables. The least significant means program in SAS (SAS Institute, 1999) was used to determine differences among treatment means at the 5% probability level.

Results and Discussion

None of the treatments tested resulted in visible damage to apple fruit or leaves over the course of the study. Bitter pit was not observed on any of the apples at harvest, including those in the control treatment. Because the primary objective was to determine where Sr was distributed, the lack of bitter pit incidence did not affect the outcomes of the study and achievement of experimental objectives.

Strontium treatments did not affect fruit fresh or dry weights, except for core samples expressed on a dry weight basis at the September sampling date. The significant Sr treatment effect for core tissue was due to higher core dry weight for Sr applications on uncovered fruit with four sprays (6.0 g) compared with all other treatments (range was 2.6 g for Sr without adjuvant, uncovered fruit, eight sprays to 4.3

Table 1. Fruit core, flesh, peel, and whole fruit (core + flesh + peel) fresh and dry weights in July and September (averaged over all Sr treatments).

Sampling date	Fresh wt (g/fruit)				Dry wt (g/fruit)			
	Core	Flesh	Peel	Fruit	Core	Flesh	Peel	Fruit
22 July	14.7	32.0	7.2	53.9	2.0	4.0	1.2	7.2
23 Sept.	24.0	101.8	15.6	141.4	3.6	14.5	2.7	20.8
Significance ^a	**	**	**	**	**	**	**	**

^aSignificant at $P = 0.01$.

Table 2. Effect of Sr treatments on leaf Sr and Ca concentrations in July and October.

Sampling date	Treatment	Sr (mg·kg ⁻¹)	Ca (g·kg ⁻¹)
22 July	Control	25 g	13.6 b ^a
	Sr without adjuvant, eight sprays	2442 e	14.4 ab
	Sr with adjuvant, eight sprays	3787 c	11.9 d
	Sr with adjuvant, four sprays ^b	19 h	12.4 cd
1 Oct.	Control	28 f	14.6 ab
	Sr without adjuvant, eight sprays	5239 b	15.1 a
	Sr with adjuvant, eight sprays	6706 a	13.1 bc
	Sr with adjuvant, four sprays	2889 d	13.3 bc

^aMeans within a column followed by the same letter are not significantly different at $P = 0.05$ using least significant means.

^bSr treatments were applied after the July sampling date.

Table 3. Fruit core, flesh, peel and whole fruit (core+flesh+peel) calcium concentration (mg kg⁻¹) and content (mg) in July and September (averaged over all Sr treatments).

Sampling date	Ca concn (mg·kg ⁻¹ dry wt)				Ca content (mg/fruit)			
	Core	Flesh	Peel	Fruit	Core	Flesh	Peel	Fruit
22 July	1324	297	740	660	2.6	1.2	0.9	4.7
23 Sept.	1074	200	507	388	3.7	2.8	1.3	7.8
Significance	**	**	**	**	**	**	**	**

^aSignificant at $P = 0.01$.

g for Sr with adjuvant, uncovered fruit, eight sprays; the control core dry weight was 2.9 g). Reasons for this effect are not known, but the lack of a clear pattern due to Sr treatment on core dry weight suggests that the effect was circumstantial. Because total fruit fresh and dry weights were not affected by treatment, the means presented are an average over all Sr treatments at each harvest date (Table 1). As expected, fresh and dry weights of all tissue parts sampled were greater in September than in July. At both sampling dates, the highest proportion of biomass was in the flesh followed by core and then peel.

Covering fruit during spray application did not affect, and was not expected to affect, Ca or Sr concentrations in leaves. Therefore, covered and uncovered data were pooled to determine Sr and adjuvant treatment effects on leaf Ca and Sr (Table 2). Sampling date and treatment effects, as well as the sampling date by treatment interaction, were significant for leaf Sr. Therefore, interaction effects are presented in Table 2. In July, leaf Sr concentrations were about 1.5 times higher when the adjuvant was used in the spray mixture compared with when the adjuvant was not included in the mixture. Strontium had not been applied to the late season treatments at the time of the July sampling and, therefore, these two treatments were comparable with controls up to this point in the study. In October, the eight Sr applications with adjuvant resulted in the highest leaf Sr concentrations, followed by eight Sr applications without adjuvant. The four late season sprays with adjuvant resulted in leaf Sr concentrations that were less than half the leaf Sr concentrations when full season sprays with adjuvant were used. In addition, four early Sr sprays with adjuvant (from the full season treatments) resulted in higher leaf Sr concentrations in July compared with leaf Sr concentrations in October from four late season applications. These results suggest that leaf absorption of Sr may be more efficient during the first half of the growing season compared with the second half. Alternatively, leaf dry matter may have been greater in October than in July, which would tend to have a diluting effect on Sr concentrations.

In the control treatment, concentrations of Ca in leaves were about 500 times greater than

Sr concentrations at both sampling dates. In addition, both elements tended to have higher concentrations in October than in July. The effect of Sr and adjuvant treatments on leaf Ca concentrations, although significant, cannot be easily explained (Table 2). There was a trend for leaf Ca concentrations to be lower when applications of Sr and adjuvant were used. However, at the July sampling date, the late season treatments had not been applied, so concentrations should have been similar to the true control but were lower. Of interest is the fact that leaf Sr in this treatment was also lower than leaf Sr in the true control and was analogous to the Ca response.

Strontium treatments had no effect on fruit Ca concentrations or content in July or at harvest. Therefore, only the sampling date effect is presented in Table 3. Fruit Ca concentrations were lower at harvest (23 Sept.) than in July. In contrast, fruit Ca content was higher at harvest than at the July sampling date. Consistent with previous reports (Tomala et al., 1989), these results suggest that Ca uptake was still occurring after the July sampling, but that biomass accumulation was occurring at a higher rate and resulted in a lower Ca concentration in all fruit parts. Calcium concentrations were highest in the core, intermediate in the peel, and lowest in the flesh tissue. The highest fruit Ca content in July and September was in the core and lowest in the peel, reflecting lower biomass accumulation in peel compared to flesh tissue (Table 1).

Strontium concentration and content in all fruit parts individually and combined were significantly affected by treatment, sampling date, and the sampling date by treatment interaction (Table 4). The main source of the interaction was the late season spray treatments, where low Sr in fruit tissue in July was due to the fact that the actual treatments were not initiated until after the sampling date. Fruit Sr concentrations increased with Sr applications for both the July and September sampling dates. The extent of this increase in Sr concentration depended on adjuvant, whether the fruit was sprayed directly or not, and timing of application. At each sampling date, core, flesh, and peel Sr concentrations were about 2 to 2.5 times higher when the adjuvant was used compared with when the adjuvant was not used. Fruit that

were not covered during Sr application had 6 to 10 times higher Sr concentrations than those that were covered. The late season treatments in July were similar to the control treatments, because late season applications had not yet begun at the time of sampling. These results reinforce the importance of directly spraying the fruit and using a suitable adjuvant to increase fruit Ca levels. Of interest, however, is that translocation from leaf to fruit tissue did occur, although the amounts were relatively low compared with direct application to the fruit. At harvest, eight Sr applications with adjuvant resulted in fruit Sr concentrations that were about three times higher compared with four late season applications with adjuvant.

As with fruit Sr concentrations, fruit Sr content increased with Sr treatments on both the July and September sampling dates and depended on adjuvant, whether the fruit was sprayed directly or not, and timing of application (Table 4). At the July sampling date, the content of Sr in core, flesh, and peel tissue was about 1.5 times higher when the adjuvant was used compared with when the adjuvant was not used. Fruit that were not covered during application had 6 to 8 times higher Sr content than those that were covered (note again that late season application treatments had not yet been sprayed in July and therefore they were comparable to controls up to this point). These results show that some translocation of Sr from leaf to fruit tissue occurs, but the amounts are relatively low compared with direct application to the fruit. Of the total Sr in fruit in July or September, 11% to 17% came from translocation from sprayed leaves and the remainder was from direct application to the fruit.

Eight spray applications with adjuvant resulted in a fruit Sr content that was about two times higher compared with four late season applications with adjuvant. Of interest, however, is that four sprays late in the season resulted in higher fruit Sr content than four sprays early in the season. In part, the advantage of later season applications is a larger apple surface area for absorption. However, even in the covered treatments, Sr content was higher in fruit given four late applications compared

Table 4. Effect of Sr treatments on Sr concentration (mg·kg⁻¹) and content (μg) of fruit core, flesh, peel, and whole fruit (core + flesh + peel).

Sampling date	Treatment	Sr concn (mg·kg ⁻¹ dry wt)				Sr content (μg/fruit)			
		Core	Flesh	Peel	Fruit	Core	Flesh	Peel	Fruit
22 July	Control	2.1 g ^z	0.6 f	1.3 g	1.1 e	4 f	3 i	2 h	9 i
	Sr, no adjuvant, fruit covered, eight sprays	11.2 f	4.0 e	15.0 f	7.8 d	26 e	19 g	22 g	67 g
	Sr, no adjuvant, fruit uncovered, eight sprays	80.0 b	28.1 b	117.6 c	58.7 b	186 b	121 d	164 de	471 de
	Sr, with adjuvant, fruit covered, eight sprays	22.3 d	8.5 d	27.9 e	15.8 cd	39 d	29 g	33 fg	101 g
	Sr, with adjuvant, fruit uncovered, eight sprays	172.7 a	71.3 a	271.6 ab	136.7 a	262 b	197 c	259 cd	718 cd
	Sr with adjuvant, fruit covered, four sprays ^y	1.9 g	0.7 f	1.3 g	1.1 e	4 f	3 i	1 h	8 i
	Sr with adjuvant, fruit uncovered, four sprays ^y	2.0 g	0.8 f	1.3 g	1.2 e	4 f	3 i	2 h	9 i
23 Sept.	Control	2.2 g	0.4 f	1.2 g	0.8 e	6 f	5 h	3 h	15 h
	Sr without adjuvant, covered, eight sprays	16.7 e	4.8 e	18.7 ef	8.5 d	51 d	80 ef	62 f	192 f
	Sr without adjuvant, uncovered, eight sprays	83.0 b	37.6 b	133.0 c	59.7 b	211 b	460 b	383 bc	1053 bc
	Sr with adjuvant, covered, eight sprays	42.1 c	13.1 c	48.8 d	22.2 c	129 c	175 cd	115 e	419 e
	Sr with adjuvant, uncovered, eight sprays	174.6 a	78.5 a	428.1 a	147.7 a	736 a	827 a	933 a	2495 a
	Sr with adjuvant, covered, four sprays	15.2 ef	3.2 de	17.4 ef	6.9 d	54 d	50 f	48 f	152 f
	Sr with adjuvant, uncovered, four sprays	39.0 c	28.5 b	211.7 bc	49.6 b	234 b	450 b	526 b	1209 b

^zMeans within a column followed by the same letter are not significantly different at *P* = 0.05 using least significant means.

^ySr treatments were applied after the July sampling date.

with fruit with four early applications. This suggests higher translocation later in the season. It is also possible that because some fruit were removed after the first four sprays, there may be a bias in comparing fruit Sr content in September from the last four sprays with fruit Sr content in July from the first four sprays. The highest Sr content for Sr sprayed treatments in July was generally found in the core and lowest was in the flesh. In September, for Sr sprayed treatments with fruit uncovered, highest Sr content was generally in the flesh or peel. When fruit was covered, there was no distinct trend in Sr distribution within the fruit.

In the control treatments, fruit Sr concentrations (on a weight basis) were about 600-fold lower than Ca concentrations in July and about 500-fold lower in September (Tables 3 and 4). Despite the large difference in concentrations, Sr distribution was similar to Ca with the highest Sr concentrations in the core and lowest concentrations in the flesh. Similarly, on a content basis, distribution of Sr in control fruit was similar to Ca distribution at both sampling dates with the highest Sr content in the core and lowest in the peel. At the July sampling date, 18%, 33%, and 49% of the fruit Sr was in the peel, flesh, and core, respectively. For comparison, 19%, 26%, and 55% of the fruit Ca was in the peel, flesh, and core, respectively. At the September sampling date, 23%, 35%, and 43% of the fruit Sr was in the peel, flesh, and core, respectively. For comparison, 17%, 36%, and 47% of the fruit Ca was in the peel, flesh, and core, respectively. These results further support the idea that Sr is a suitable tracer for Ca.

Although Sr distribution in apple fruit was similar to Ca distribution, discrimination between Ca and Sr transport may still exist. Discrimination between Sr and Ca transport has been defined as the ratio of Sr to Ca in plant tissue relative to the ratio of Sr to Ca in soil extracts (Martin et al., 1958):

$$\left(\frac{\text{Sr}_{\text{plant}}}{\text{Ca}_{\text{plant}}} \right) / \left(\frac{\text{Sr}_{\text{soil}}}{\text{Ca}_{\text{soil}}} \right) \quad [1]$$

Values less than one indicate discrimination against Sr. Higher retention of Sr compared with Ca was found in stem tissue of barley (Martin et al., 1958) and wheat (Smith, 1971). Soil Ca concentrations of 2202 mg·kg⁻¹, soil Sr concentrations of 4.5 mg·kg⁻¹, leaf Ca and Sr concentrations from the controls in Table 2, fruit Ca concentrations from Table 3, and fruit Sr concentrations from the controls in Table 4 were used to calculate discrimination values for this study. Ratios of 0.82 (July) to 1.16 (September) were found for fruit tissue and 0.90 (July) to 0.94 (October) for leaf tissue. Because of the potential discrimination between Sr and Ca during transport, it is not possible to unequivocally conclude that Sr distribution in fruit from foliar and fruit applications would be exactly the same as Ca applications. However, based on Ca and Sr distribution and discrimination values in the controls, it is likely that transport of foliar and fruit-applied Sr and Ca is similar.

Results of this study clearly show that fruit Sr can be increased by Sr applications to leaves and fruit and that increases are due to both translocation to the fruit from foliar applica-

tions as well as direct penetration of the peel and subsequent movement to flesh and core tissue. In contrast, studies with ⁸⁵Sr applied to leaves and fruit to simulate radioactive fallout have shown little translocation to fruit (Carini and Bengtsson, 2001). Accumulation of radioactivity in apple fruit was restricted to the peel and was the result of direct application to the fruit (Bengtsson, 1992). Similarly, Van Goor (1973) reported little penetration of ⁴⁵Ca below the skin when applied to the surface of apple fruit. Nine days following application, most of the radioactivity was found within a 1-mm section below the skin. The studies using ⁸⁵Sr were conducted with high radioactive counts, but very low concentrations of Sr (<0.012 mg·L⁻¹ Sr). This concentration is about 250,000 times less than the 3080 mg·L⁻¹ Sr (35 mM) used in our studies, which was selected to simulate Ca concentrations routinely recommended for foliar application. For the radioactive Ca studies, the ⁴⁵Ca was mixed with a high concentration of Ca, but only a 10-μL drop was applied to the fruit surface. In contrast, the high concentrations of Sr used in our study were applied to leaves and fruit until runoff.

The results from the ⁸⁵Sr and ⁴⁵Ca studies and the foliar and fruit applied Sr study presented here are all consistent with Ca transport processes in plants. Movement of Ca is directly linked to cation exchange processes in the xylem vessels and cell walls of the surrounding tissue (Marschner, 1995). Low concentrations of Sr or Ca are likely adsorbed by leaf and peel cell walls and do not move significantly to leaf xylem tissue or to inner parts of the fruit. Similarly, low volumes of high Ca concentrations applied to the fruit surface would also be adsorbed by cell walls before penetrating deeply below the skin. Known methods to induce transport of foliar-applied Ca include increasing the concentration of Ca in the spray solution, adding a chelating agent, injuring the leaf, adding other divalent cations to the spray solution, and increasing the volume of spray solution applied (Hanger, 1979; Swietlik and Faust, 1984). The high Ca concentrations and volumes used in foliar sprays to control bitter pit will tend to saturate the system and minimize the effects of cation exchange reactions, thus allowing movement beyond surface tissue. The distribution of Sr in apple fruit found in the present study was likely the result of saturating exchange sites and allowing transport into the tissue from sprayed leaves, as well as direct penetration through the peel.

Assuming that Sr transport is similar to Ca transport, an estimate of the maximum Ca increase in fruit tissue from foliar and fruit applications can be calculated from the Sr data presented in Table 4. Because Sr has an atomic weight of about 2.2 times that of Ca, the concentration of Ca in fruit (mg·kg⁻¹ Ca dry weight) will actually be less than the concentration measured using Sr. Adjusting for the molecular weight of Ca, and based on the observed increase with Sr, the maximum increase in fruit Ca concentration (dry weight basis) from foliar applications (eight sprays with adjuvant and uncovered fruit) was as fol-

lows: core, 78 mg·kg⁻¹ Ca; flesh, 35 mg·kg⁻¹ Ca; peel, 195 mg·kg⁻¹ Ca; entire fruit, 67 mg·kg⁻¹ Ca. On a content basis, Ca would increase by about 1.1 mg per fruit with an average fresh weight of about 140 g. This estimate is lower than those reported by Van Goor (1971), but within the range reported for Ca applications by Wilkinson (1968).

In conclusion, results from this study suggest that Sr is a suitable tracer for foliar- and fruit-applied Ca in apple trees. The advantage of using Sr is derived from background levels of Sr in soil and plant tissue that are much lower than Ca levels. Of the total Sr in fruit, about 11 to 17% can be attributed to translocation from sprayed leaves, confirming that direct spray application to fruit is essential for maximum increases in fruit Sr. Eight spray applications over the growing season more than doubled the concentration and content of fruit Sr compared with four late season sprays. The adjuvant used in this study doubled Sr absorption by and translocation to fruit compared with no adjuvant. Use of Sr instead of Ca in research trials may provide a more precise method of evaluating the efficacy of different adjuvants to increase fruit Ca.

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