Changes in Spray Retention by Apple Leaves during a Growing Season

Franklin R. Hall¹, Roger A. Downer¹, Jane A. Cooper¹,
Timothy A. Ebert¹, and David C. Ferree²

The Ohio Agricultural Research and Development Center, The Ohio State University, Wooster, OH 44691

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Abstract. Apple (*Malus domestica* Borkh.) leaves were sprayed to runoff using a selection of pesticides, and subsequent spray retention was evaluated by weight. Timing, cultivar, leaf surface, and leaf type significantly influenced spray retention. Spray retention correlated significantly and positively with leaf hair density. The importance of these differences is considered in relation to the possible efficiency of the pesticide application process in apple orchards.

Chemicals can be applied to apple trees six to 15 times per year for protection against diseases and arthropod pests, and to influence fruit abscission. Target leaves and canopy geometry in apple orchards change greatly during a single growing season. Typically, when the first spray (excluding dormant sprays) of the season is applied, the canopy consists of newly emerged spur leaves from previously dormant buds. These spur leaves comprise the majority of the canopy until shortly after bloom (Rom and Ferree, 1984). In contrast, when midseason sprays are applied, each tree has its full complement of fully expanded leaves, with shoot leaves contributing proportionately more than spur leaves to leaf area due to their larger sizes and greater numbers on a tree (Forshey et al., 1987). At the end of the season, leaves become senescent and abscise. In addition to the physiological changes occurring in the canopy, leaf structure is continually modified by the environment. Leaves are abraded by both weather and other leaves, and attacks by pests and diseases can alter their surface structure.

Furmidge (1962) found that macrostructure of the leaf affected liquid retention, and leaf hairs trap liquid and prevent it from running off the leaf. Ennis et al. (1952) found that pubescent soybean plants retained more spray than glabrous ones. Therefore, the number and condition of the leaf hairs (= leaf pubescence or trichomes) presumably affect spray retention. Indeed, any parameter that alters the leaf surface during a growing season is likely to affect the efficiency with which the chemical

is captured and retained. For a chemical to be efficacious, sufficient spray droplets must be retained by, and distributed on, the leaves.

The objective of the primary study reported here was to investigate spray retention by apple leaves at different times during a growing season. Differences in retention by shoot vs. spur leaves, adaxial vs. abaxial leaf surfaces, of four cultivars are reported at three timings. A preliminary additional study of leaf hair density $\times$ retention interactions is also reported.

Materials and Methods

Spray retention (Expt. 1)

Experimental design. The experimental design for the retention study was a completely randomized $4 \times 2 \times 2 \times 3 \times 7$ factorial with four cultivars, two leaf types, two leaf surfaces, three experiment timings, and seven pesticide treatments, including water control. Eight measurements of spray retention were made for each treatment.

Sample collection. Leaves were collected from 9-year-old trees of 'Smoothie Golden Delicious', 'Oregon Spur Delicious', 'Empire', and 'Lawspur Rome Beauty' at three times during the 1990 growing season, viz., post petal-fall (May), full foliage (July), and preharvest (October). Shoots and spurs were selected at random from branches ≈ 1.5 m above ground on all sides of individual trees, but the fifth leaf from the base of a shoot was always sampled, as was the fifth leaf in the rosette pattern of any spur. Leaves were stored flat in plastic bags in the laboratory until sprayed.

Pesticide treatments. Six pesticides (three emulsifiable concentrates and three wettable/dry flowable powders) were chosen as representative of pesticides presently used by orchard growers and were applied at concentrations within the recommended rate range. Pesticides sprayed were fenvalerate (Pydrin 2E), permethrin (Ambush 2E), fenarimol (Rubigan EC), myclobutanil (Nova W), benomyl (Benlate DF), and maneb (Manzate DF) at 0.625, 0.318, 0.234 mL/L⁻¹, and 0.117, 0.225,

and 2.397 g/L⁻¹, respectively. Tap water was applied as a control.

Treatments were applied from a 200-mL reservoir through a single Teejet 8001-E fan nozzle at 276 kPa (40 psi). The sprayer remained stationary throughout the test. Adaxial leaf surfaces were sprayed for 15 s and the abaxial surfaces for 20 s; preliminary experiments established that these times were sufficient for runoff.

Spraying protocol. Immediately before spraying, the mass of each leaf was determined to the nearest mg using a Mettler PM460 precision balance (Mettler Instrument Corp., Hightstown, N.J.).

Four leaves, positioned 5 cm apart, were mounted horizontally on a leaf support using a pin placed through each leaf petiole. The leaf tip was positioned slightly lower than the petiole, at an $\approx 10^\circ$ angle, to encourage liquid to leave the leaf at the tip rather than at the sides. The leaf support was fabricated from a 25×3 -cm piece of wood covered with 1-cm-thick polystyrene to facilitate the removal of pins. Leaves were placed on the support such that the midrib of the leaf was perpendicular to the long axis of the support. The leaf support was placed in an environmental spray chamber (Research Instrument Mfg., Guelph, Canada) on a rigid mesh platform. The support was positioned 40 cm below a single nozzle, parallel to the long axis of spray cloud, and with the middle point of the support aligned centrally underneath the nozzle.

For each pesticide, four leaves were sprayed at a time, one from each cultivar. The position of each cultivar relative to the nozzle was changed at successive applications to minimize variation due to any unevenness of the swath pattern. Eight replicate sprays of each pesticide were applied and this procedure was repeated for the adaxial and abaxial surfaces of both shoot and spur leaves, giving a total of 32 leaves from each cultivar for each pesticide.

After spraying, the leaf support was carefully removed from the spray chamber so as not to dislodge any excess spray remaining on the leaves. The support was then rotated so that the leaves hung vertically, and clamped 20 cm in front of a box-fan producing a wind speed of approximately 3 m s^{-1} (Dwyer wind meter; Michigan City, Ind.). This was to simulate an orchard situation where leaves are usually moved after spraying, either naturally by air currents, or from the air blast of the sprayer itself. Each leaf was reweighed after 30 s of simulated air currents.

After each leaf was weighed, leaf area was measured using a Li-3000 portable area meter (LI-COR, Lincoln, Neb.). The average leaf area throughout the study was $\approx 18 \text{ cm}^2$. Spray retention was expressed as the quantity of deposit retained per unit area of leaf (mg cm^{-2}).

Leaf hair study (Expt. 2)

To estimate the density of leaf hairs, an area of leaf (1 mm^2) was examined under a binocular microscope and the number of leaf hairs counted. Areas containing large veins

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¹Laboratory for Pest Control Application Technology.

²Dept. of Horticulture.

were avoided. At low densities the number of hairs could be determined accurately; however, when the leaf hairs were very dense, the numbers were estimated because individual hairs were intertwined and difficult to distinguish. Eighteen, 15, and 10 individual counts of leaf hair density were made from each cultivar, leaf surface, and type in May, July, and October, respectively.

Statistical analyses. For the retention study, analysis of variance (ANOVA) was performed on the raw spray retention data. For the leaf hair study, ANOVA was performed on the number of leaf hairs (Proc GLM; SAS Institute, Cary, N.C.). The effect of leaf hairs on retention was investigated using regression analysis.

Results and Discussion

All of the main factors (timing, leaf surface, leaf type, and cultivar) significantly influenced spray retention (Table 1). Differences between the retention of the various pesticides were reported previously (Cooper and Hall, 1993). Many interactions, including three of the four-way interactions, were also significant; however, few of these interactions

explain much of the variability within the data. The most interesting main effects and interactions, in order of importance, were leaf surface, cultivar, leaf surface $\times$ cultivar, timing, pesticide, and timing $\times$ leaf surface.

Timing. The amount of spray retained over all cultivars, leaf types, and leaf surfaces decreased at each application, with 30% more being retained at the start of the season than at the end; this was associated with a 60% decrease in the number of leaf hairs during the study, with the density decreasing most from July to October (Table 2). The retention study data also showed that the amount of spray retained on the abaxial surface remained fairly constant over the season, but that retention on the adaxial surface decreased with time.

In the 5 months between the first and last spray applications, apple leaves would have undergone many changes. Some changes would have been physiological as leaves changed from newly emerged, to mature, to presenescent; others would have been environmental, e.g., abrasion of the leaves by insects or other leaves, damage by pests or disease. Other authors have reported changes in pesticide retention with leaf age, and that the

effect was species specific. Verity et al. (1981) showed spray retention to be less on old than on young onion plants, but that retention did not change appreciably with age for three weed species. Bukovac et al. (1979) found that chemical composition of and pesticide retention on a peach leaf surface changed as leaves aged; retention of an aqueous solution decreased with leaf expansion. Baker (1974) noted that environmental conditions can modify the size and distribution of surface wax structure, and that more wax was generally deposited under conditions of high radiant energy. In many species, the epicuticular wax system of young leaves is less well developed than that of older leaves, and the quantity of wax increases with leaf age (Boize et al., 1976; Bukovac et al., 1979; McWhorter et al., 1993; Verity et al., 1981). Structured hydrophobic waxes also may have accumulated on the apple leaves in our study, resulting in lower retention of sprays as the season progressed. We found a consistent reduction in leaf hair density over the season, which was most pronounced between July and October (Table 2).

Leaf surface. The parameter that had the largest effect on spray retention was leaf surface (Table 1). Significantly more spray was retained on the abaxial than on the adaxial surface. This was associated with a much denser covering of leaf hairs on the former (Table 2). As noted earlier, pubescent soybean leaves retain more spray than glabrous ones. In this study, regression analysis relating leaf hair density to retention of pesticides gave an R^2 of 0.52 ($P > F < 0.001$), suggesting that leaf hairs also play an important role in pesticide retention by apple leaves. A further study is planned specifically to investigate this relationship.

The microstructure of the two surfaces also probably influenced spray retention. Bukovac et al. (1979) showed that the two surfaces of peach leaves differed markedly in the composition of epicuticular wax, and Anderson et al. (1987) noted that the abaxial surface of wheat leaves was devoid of crystalline wax, whereas the adaxial surface was covered with platelets. The surfaces of the apple leaves were not characterized either micro- or macroscopically, but they were easy-to-wet and when sprayed with an aqueous spray, none of the impacting droplets rebounded from either surface. During the season, spray retention

Table 1. Analysis of variance table for raw spray retention data showing the main effects and all interactions.

Source of variation	df factor	SS factor	F value	$P > F$
Timing	2	0.00300	36.19	0.0001
Pesticide	6	0.00182	7.33	0.0018
Surface	1	0.03103	634.59	0.0001
Timing $\times$ surface	2	0.00164	16.82	0.0003
Surface $\times$ pesticide	6	0.00019	0.66	0.6822
Type	1	0.00024	25.73	0.0001
Timing $\times$ type	2	0.00006	3.19	0.0546
Pesticide $\times$ type	6	0.00016	2.85	0.0243
Surface $\times$ type	1	0.00057	60.80	0.0001
Cultivar (cv)	3	0.00984	576.48	0.0001
Timing $\times$ cv	6	0.00049	14.29	0.0001
Pesticide $\times$ cv	18	0.00017	1.62	0.0476
Surface $\times$ cv	3	0.00889	521.24	0.0001
Type $\times$ cv	3	0.00011	6.71	0.0002
Timing $\times$ pesticide $\times$ cv	36	0.00035	1.69	0.0065
Timing $\times$ surface $\times$ cv	6	0.00057	16.68	0.0001
Timing $\times$ type $\times$ cv	6	0.00012	3.45	0.0022
Surface $\times$ treatment $\times$ cv	18	0.00017	1.64	0.0435
Pesticide $\times$ type $\times$ cv	18	0.00012	1.18	0.2720
Surface $\times$ type $\times$ cv	3	0.00007	4.20	0.0057
Timing $\times$ surface $\times$ pest. $\times$ cv	36	0.00035	1.72	0.0053
Timing $\times$ pest. $\times$ type $\times$ cv	36	0.00031	1.52	0.0251
Timing $\times$ surface $\times$ type $\times$ cv	6	0.00013	3.71	0.0011
Surface $\times$ pest. $\times$ type $\times$ cv	18	0.00012	1.18	0.2657
Tim. $\times$ sur. $\times$ pest. $\times$ type $\times$ cv	36	0.00026	1.28	0.1264

Table 2. Influence of timing, leaf surface, leaf type, and cultivar on spray retention by apple leaves, and associated leaf hair density measurements.

Factor	Spray retention (mg·cm ⁻²)			Leaf hair density (hairs/cm ²)		
	May	July	Oct.	May	July	Oct.
Timing	0.008	0.007	0.006	24.1	21.1	9.8
Surface						
Abaxial	0.011	0.012	0.009	44.8	41.0	19.1
Adaxial	0.006	0.003	0.002	3.3	1.0	0.4
Type						
Shoot	0.009	0.008	0.006	27.6	26.7	10.6
Spur	0.008	0.007	0.006	20.5	15.4	8.9
Cultivar						
Empire	0.010	0.010	0.010	37.4	33.4	16.1
Oregon Spur	0.009	0.008	0.006	31.4	23.5	12.9
Lawspur	0.007	0.006	0.004	14.4	15.2	4.2
Smoothie	0.007	0.005	0.004	13.0	12.1	5.8

Table 3. Comparison of shoot and spur leaves during the growing season.

Leaf	May		July		October	
	Fresh mass (g)	Leaf area (cm ²)	Fresh mass (g)	Leaf area (cm ²)	Fresh mass (g)	Leaf area (cm ²)
Shoot	0.629 a ²	23.2 a	0.653 a	22.5 a	0.639 a	22.6 a
Spur	0.300 b	10.4 b	0.393 b	13.7 b	0.415 b	14.9 b

²Mean separation within columns by F test, $P = 0.05$.

changed little for the abaxial surface, but declined more than 60% for the adaxial surface.

Leaf type. Spur leaves consistently retained slightly less spray than shoot leaves, and had fewer leaf hairs (Table 2). Shoot and spur leaves differ in form and function. Spur leaves are formed in a rosette pattern and exert an important localized influence on fruit set, size, and fruit calcium level (Ferree and Palmer, 1982). Our data confirm those of Schechter et al. (1992) in that shoot leaves were significantly more massive and larger than spur leaves at each of the three timings (Table 3). The mass and area of the shoot leaves remained constant throughout the season, but both parameters increased in spur leaves as the season progressed.

Cultivars. The cultivars retained significantly different amounts of spray. When the data were averaged over all three timings, 'Empire' leaves retained twice as much spray as 'Smoothee' leaves (Table 2). Spray retention increased through the season for 'Empire', changed very little for 'Oregon Spur', and decreased somewhat for both 'Lawspur' and 'Smoothee'. Retention again followed the trend of leaf hair density, with greater pubescence corresponding to greater spray retention. There were probably microscopic and ultramicroscopic differences between cultivars in addition to the macroscopic differences of pubescence, and the extent to which veins were recessed or raised in relation to surrounding leaf surface. For example, the size and shape of grooves between epidermal cells, and the size, shape, and organization of the epicuticular wax system can all change the retention capability of leaves.

Conclusions

The overall retention decreased at each subsequent application during the season, and the four cultivars retained significantly different amounts of spray. Spray retention per unit area of leaf was significantly higher on the lower than the upper leaf surface, and on shoot leaves vs. spur leaves. Preliminary investigation showed that spray retention correlated well with leaf hair density.

As foliage (leaf area index) increases during the season, the requirements for increased spray volumes require grower awareness and adjustments in sprayer calibrations and nozzle settings. Coverage difficulties can be managed, if cultivar retention differences as well as cultivar tolerances to specific pests in a spatial/temporal context are considered. The data from this study indicate that block by block adjustments in apple orchards, with complex pest dynamics, is a necessary practice if optimization of crop protection is to be achieved.

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