Pesticide Spraying in Indian River Grapefruit: III. Opportunities for Improving Efficacy and Efficiency while Reducing Off-target Deposition

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SUMMARY. **Parts I and II of this series revealed substantial opportunities for improving spraying of Indian River citrus (*Citrus* spp.). In this segment of our work we develop guidelines for growers to select the spray parameters providing an optimal balance between efficiency and efficacy while minimizing environmental contamination. It is proposed that these guidelines could be codified in a simple expert system to make them easier to use. We propose that understanding limiting conditions may be the key to choosing spray options. Wind is a major factor influencing spray deposition and off-target drift. Based on weather records, wind speeds below 5 mph (8.0 km·h^{-1}) are only routinely observed from 2000 HR until 0800 HR, making night spraying a good choice for low-volume applications. The importance of adjusting sprayer set-up for individual groves is demonstrated, with economic estimates of the cost of failing to make these adjustments. Routine use of careful sprayer adjustments is also likely to reduce off-target drift. Improvements in equipment and spray chemicals are also discussed. Use of non-orchard buffer areas and/or windbreaks appear to offer considerable opportunity for reducing off-site spray movement.**

Indian River (IR) citrus growers are confronted with numerous pests and an environment conducive to disease development, in addition, citrus trees are also some of the most difficult of all tree crops to spray effectively (Carman and Jeppson, 1974; Juste et al., 1990). Environmental influences, such as wind and humidity, combine with large canopy size and limitations of sprayer capabilities to make spray coverage much less than ideal. A significant proportion of grapefruit (*Citrus paradisi*) are excluded from the more profitable fresh market [81% for white grapefruit and 50% for red grapefruit in 2001–02 (Ritenour et al., 2003)], due to cullage resulting from poor disease control, and other cullage due to wind damage and other factors unrelated to the spray program. Since culled fruit may or may not have value for processing, it is especially difficult to determine the economic balance between reducing spraying costs and the use of more thorough spraying that may increase the proportion of fruit sold for fresh-market prices. Market fluctuations further complicate effective planning, since growers cannot predict the relative values of fresh and processed fruit prior to the spray season.

Not only do economic concerns compel a reevaluation of spray practices, but better spray retention on trees, less non-target deposition, and less drift may be environmentally beneficial. Recent concerns about the long-term health of the IR Lagoon and St. Lucie Estuary have focused attention on pollutants associated with citrus production. The potential influence is substantial, since citrus covers 42% of the land area in the 288,000-acre (116,554 ha) St. Lucie drainage basin and 19% of the 1.2 million-acre (0.49 million ha) drainage basin of the IR Lagoon (Indian River Lagoon National Estuary Program, 1996). About 45% of the IR citrus acreage is used in production of grapefruit (Florida Agricultural Statistics Service, 2003).

As described in parts I and II of this series (Stover et al., 2002, 2003a), intensive assessment of IR spray application practices has been stimulated by these economic and environmental concerns. Part I presented information from a 2001 survey of IR citrus spraying practices and part II explored and summarized relevant literature to provide an understanding of factors influencing spray efficacy and off-target deposition. In this document, current spray practices are assessed in the context of published research to outline opportunities for improving economic efficiency and reducing potential environmental impact. Several of the most important research needs relating to spray efficacy and off-target deposition are also discussed.

Overview of grapefruit spraying

To critically evaluate opportunities for improving spray applications, the objectives of IR grapefruit spray programs must first be established. Fungal diseases affecting rind appearance are among the most important causes of IR grapefruit cullage in the packing house, so protection of the fruit surface is of primary importance, to minimize fruit blemishes. There are three main fungal pathogens that damage the rind of grapefruit: citrus scab (caused by *Elsinoe fawcettii*), melanose (caused by *Diaporthe citri*), and greasy spot (caused by *Mycophaerella citri*). The control of these diseases provides the structure for spray programs throughout the entire growing season. Disease control programs for these three pathogens are supplemented by sprays for arthropod pests, largely mites [primarily citrus rust mite (*Phyllocoptruta oleivora*)]; scale insects, over 40 species of which infest Florida citrus [the most important include Florida red scale (*Chrysomphalus aonidum*), soft brown scale (*Coccus hesperidum*), purple scale (*Cornuaspis becki*), cottonycushion scale (*Icerya purchasi*), glover scale (*Lepidosaphes gloveri*), chaff scale (*Parlatoria pergandii*), Caribbean black scale (*Saissetia neglecta*), and citrus snow scale (*Unaspis citri*)]; other fungi (predominately *Colletotrichum acutatum*, *Alternaria citri*, and *Phytophthora nicotianae*), and foliar nutrients as needed. Most of the fungicidal materials used in Florida citrus must be applied before disease symptoms occur, since they serve as protectants against new infection but have little influence on established infections (Whiteside, 1977). The grower begins a program of typically four to eight sprays beginning at bloom (March–April) and continuing until late summer (Indian River

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citrus growers, personal communications; Muraro et al., 2002).

As with all diseases, infection only occurs when both susceptible tissue and inoculum are present and environmental conditions are favorable for inoculum dispersal and infection. Prolonged shoot growth in IR citrus results in an extended period where canopy tissue is susceptible to some diseases. As a result, it is currently economically feasible to reduce but not eliminate foliage and/or stem infections for the most important grapefruit diseases (especially for melanose and greasy spot), and presence of considerable canopy infection is common in most orchards. Availability of registered fungicides with either systemic or potent eradicant properties could substantially change spraying strategies in IR grapefruit.

Opportunities for improved spraying using established methodology

Numerous research reports suggest that different sprayers or spray practices are likely to influence spray coverage and associated potential for drift. However, in practice it has often been difficult to demonstrate effects on pest control in controlled experiments. Researchers frequently show similar results using a wide variety of equipment or techniques (Brooks, 1969; Bullock et al., 1977; Whitney et al., 1978). Tremendous variability in spray deposition makes it difficult to effectively compare spray parameters in field trials, compromising ability to offer firm recommendations. Nonetheless, growers must make decisions about spray practices and these decisions may have pronounced effects on profitability and the extent of environmental contamination. In this section, we will attempt to integrate the available information to provide some guidance for growers making these decisions.

SPRAY VOLUME AND SPRAYER GROUND SPEED DURING SPRAYING

Lower ground speeds [1–2 mph (1.6–3.2 $\text{km}\cdot\text{h}^{-1}$)] and higher spray volumes [500–750 gal/acre (4676.8–7015.2 $\text{L}\cdot\text{ha}^{-1}$)] are generally considered conducive to most complete coverage and best potential pest control (Stover et al., 2002a), but the low efficiency of this approach may not be economical and higher total pesticide use may be necessary. Increasing ground speed and/or lowering spray volume are two ways of increasing efficiency in pesticide application.

Effects of spray volume and ground speed on efficiency. The potential benefits of lower spray volumes and higher ground speeds are apparent to a great majority of IR citrus growers. The financial incentive to use the lowest volume possible becomes clear when examining the time per acre required for the entire pesticide application process. For a given orchard, this is determined by the sprayer ground speed, tank capacity, and the volume (gallons per acre) used, since volume affects proportion of time spent spraying vs. filling. There are clear savings from spraying at a higher speed and lower volume (Table 1). In the following comparisons, assumptions include a 40-acre (16.2 ha) orchard with 900-ft (274.3 m) rows and 24 ft (7.3 m) between rows, resulting in 81 passes of 900 ft each to spray the entire orchard, plus 38 ft (11.6 m) traveled for each turn at the row ends. In each case, the cost estimates are for spray application only and do not include material costs. For comparisons in which a single

Table 1. Estimates of costs associated with different spray options. Estimates are for a 40-acre (16.2 ha) block with 24 ft (7.3 m) between rows and 900-ft (274.3 m) row length. Economic assumptions are: \$15/h for spray operator, \$50/h for sprayer operation and depreciation during spraying, \$20/h for nurse tank and operator, average drive of 2700 ft (823.0 m) to filling station at 5 mph (8.0 $\text{km}\cdot\text{h}^{-1}$), and 10 min for fill and mix after arrival at the filling station.

			Spray and fill (min/acre)[z]		Cost (\$/acre)[z]			
			1000-gal	500-gal	1000-gal sprayer		500-gal sprayer	
Sprayer (mph)[z]	Spray vol (gal/acre)[z]	Spray time (min/acre)[z]	(3785.4 L) sprayer	(1892.7 L) sprayer	Drive to source[y]	Nurse tank[x]	Drive to source[y]	Nurse tank[x]
1	500	22.4	30.4	38.4	33.0	35.3	41.6	38.9
1	250	22.4	26.4	30.4	28.6	33.6	33.0	35.3
1	125	22.4	24.4	26.4	26.5	32.7	28.6	33.6
1	30	22.4	22.9	23.4	24.8	32.0	25.4	32.2
1.25	500	18.0	26.0	34.0	28.1	29.0	36.8	32.5
1.25	250	18.0	22.0	26.0	23.8	27.2	28.1	29.0
1.25	125	18.0	20.0	22.0	21.6	26.3	23.8	27.2
1.25	30	18.0	18.4	18.9	20.0	25.6	20.5	25.9
1.5	500	15.0	23.0	31.0	24.9	24.7	33.5	28.3
1.5	250	15.0	19.0	23.0	20.5	23.0	24.9	24.7
1.5	125	15.0	17.0	19.0	18.4	22.1	20.5	23.0
1.5	30	15.0	15.4	15.9	16.7	21.4	17.2	21.6
2	500	11.2	19.2	27.2	20.8	19.4	29.5	23.0
2	250	11.2	15.2	19.2	16.5	17.7	20.8	19.4
2	125	11.2	13.2	15.2	14.3	16.8	16.5	17.7
2	30	11.2	11.7	12.2	12.7	16.1	13.2	16.3
3	500	7.5	15.5	23.5	16.8	14.1	25.4	17.7
3	250	7.5	11.5	15.5	12.4	12.4	16.8	14.1
3	125	7.5	9.5	11.5	10.3	11.5	12.4	12.4
3	30	7.5	8.0	8.4	8.6	10.8	9.1	11.0
3	30[w]	7.5	8.0	8.4	11.9	14.0	12.7	14.3

[z] 1.0 mph = 1.61 $\text{km}\cdot\text{h}^{-1}$; 1.0 gal/acre = 9.35 $\text{L}\cdot\text{ha}^{-1}$; 1.0 min/acre = 2.47 $\text{min}\cdot\text{ha}^{-1}$; \$1.0/acre = \$2.47/ha.

[y] Single employee drives to spray water source in block.

[x] Assumes that nurse tank services two sprayers at the same time.

[w] Variant at \$75/h sprayer operation and depreciation during spraying for higher maintenance equipment.

employee sprays and fills using a 1000-gal (3785.4 L) sprayer, application at 500 gal/acre and 1 mph would take 30.4 min/acre (75.12 min·ha^{-1}) and cost $33/acre ($81.54/ha); application at 125 gal/acre (1169.2 L·ha^{-1}) and 2 mph would take 13.2 min/acre (32.62 min·ha^{-1}) and cost $14.3/acre ($35.33/ha); and application at 30 gal/acre (280.6 L·ha^{-1}) and 3 mph (4.8 km·h^{-1}) would take 8 min/acre (19.8 min·ha^{-1}) and cost $8.6/acre ($21.25/ha). Since fresh grapefruit production typically involves five or more sprays per year, selection of spray application parameters may affect annual production costs by as much as $122/acre ($301.46/ha) (five times the difference in cost for 500 gal/acre at 1 mph and 30 gal/acre at 3 mph). In addition, being able to cover acreage more quickly can reduce the number of sprayers needed and thus reduce capital outlay. For example, spraying at 125 gal/acre and 1.5 mph (2.41 km·h^{-1}) could reduce the number of sprayers needed by half compared to spraying at 500 gal/acre and 1 mph (Table 1). Therefore, if similar levels of pest control can be achieved, without compromising sustainability, it makes sense to use the least expensive approach.

Effects of spray volume and ground speed on efficacy. Reported relationships between spray volume and efficacy include some seemingly contradictory elements. Much of this is from confusion in interpreting different factors measured in spray studies. A crucial distinction is that deposition refers to the percentage of spray material retained on target tissues; whereas coverage refers to the uniformity of deposition on target surfaces. Deposition is generally more important than coverage for controlling mobile pests, while good coverage is generally more important for control of non-mobile pests. As a result, low volume applications, with high deposition, are often reported to be as effective as much higher volumes in controlling mobile pests (Bullock et al., 1968; McCoy et al., 1989). When applying spray materials from the ground, there is a fairly consistent trend of increasing variability in spray deposition as spray volume is reduced from 500 gal/acre (Hoffman and Salyani, 1996; Salyani and McCoy, 1989). Similarly, residue variability increased for the tree interior as tractor speed was increased from 1 to 4 mph (1.6 to 6.4 km·h^{-1}) (maintaining constant spray volume), although total deposition was not significantly affected (Salyani, 1995). It is not obvious how to balance better coverage at higher spray volumes and lower costs from spraying at lower volumes. Because many growers are not willing to risk poor spray coverage, 28% of all IR citrus acreage is still sprayed at 450 gal/acre (4209.1 L·ha^{-1}) or higher for all sprays (Stover et al., 2002a). Since the literature shows that lowering volume increases deposition (because less material drips from trees), it has also been proposed that less total pesticide may be needed for control at lower application volumes (Steiner, 1977). Indeed, survey figures for IR grapefruit (Stover et al., 2002a) show that copper use per acre per year declines with mean spray volume used.

Efforts should be expanded to help growers understand when more expensive spray practices will not result in better returns. For example, the least expensive method for spray applications is via fixed-wing aircraft (Muraro et al., 2002). However, coverage is often limited to the outer shell of the canopy (Bullock and Brooks, 1983) making this approach inappropriate for routine control of diseases like melanose or greasy spot. This was confirmed in a study where copper sprays using ground sprayers were used to supplement an aerial application program. Supplemental ground applications often increased melanose control and apparent fruit value, except where repeated ground sprays caused copper marking (Stover et al., 2004). However, experiments such as this should be interpreted with caution since conditions conducive to pest development are often sporadic and timing of individual sprays relative to these conditions may be of greatest importance.

Additional application costs might be a good investment if increased fruit value substantially exceeds the additional costs. To put this into perspective, consider that in 2002 average total returns declined by $11 for every 1% increase in fruit elimination in a typical mature IR 'Marsh' grapefruit orchard producing about 17.8 tons/acre (39.90 t·ha^{-1}; calculated from Fla. Dept. of Citrus, 2003), with greater financial losses from more productive orchards (Fig. 1). A recent trial compared season-long spray programs in IR grapefruit with the same timings and materials, but different spray volumes and ground speeds. Trees sprayed at 250 gal/acre (2338.4 L·ha^{-1}) and 1 mph had projected fruit elimination percentages ranging from 3% to 15% lower than those observed on trees sprayed at 125 gal/acre and 2 mph (Stover et al, 2002b). These data, combined with the application cost estimates in Table 1, suggest that use of slower tractor speed and higher spray volume may be justified in high yielding orchards, but not in those producing substantially below the industry average.

In this same trial, higher speed reduced control of melanose in the tree interior in only one of two trials. In the orchard with smaller trees, there was no significant disadvantage to use of higher speeds (Stover et al., 2002b). These results were consistent with the idea that successful tree spray coverage requires a travel speed low enough to allow "complete air displacement" within the tree row, as determined by the sprayer fan air capacity, the tree volume and ground speed, (Cromwell, 1975). This recommendation is considered conservative, since additional air is entrained with the spray stream to push aside the air volume in the tree canopy (Fleming, 1962). However, this concept may still be useful for growers to estimate an appropriate sprayer ground speed (Fig. 2). Note that most IR grapefruit growers spray at 1.0 to 2.0 mph when using airblast sprayers, while some sprayers are used at up to 4.0 mph (6.44 km·h^{-1}) (Stover et al., 2002a), so growers are only likely to fall below complete air displacement when spraying very large trees.

Limitations to improving packout through selection of spray practices. In current fresh IR grapefruit production, it is rare for growers to achieve packout of even 80% of harvested fruit, and these high rates are usually found in young trees. Most mature trees, with substantial inoculum, only have 20% to 50% of fruit with acceptable cosmetic quality for fresh sale (Indian River growers, personal communication). This certainly suggests that better spray coverage could increase packouts, but may be somewhat misleading since windscar is often the largest cause of fresh fruit elimination (Miller and Burns, 1992) and poor shape unrelated to spray practices can be a serious source of eliminations in some years (Indian River growers, personal communication). In addition, many fruit that are

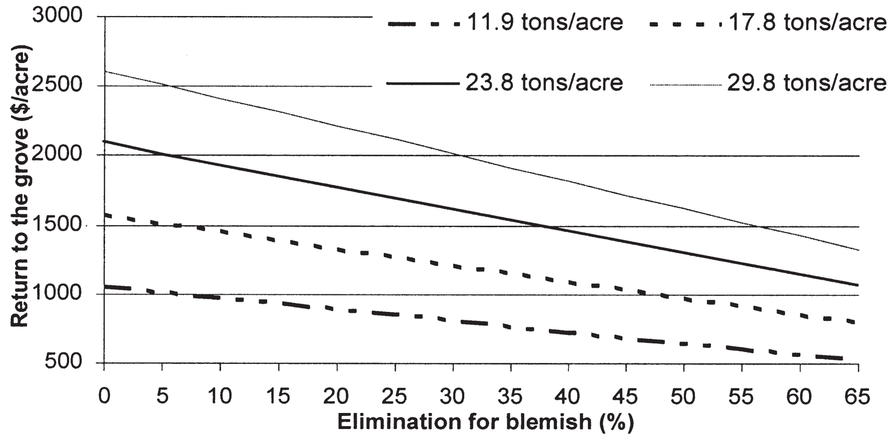

Fig. 1. Economic returns for Florida 'Marsh' grapefruit as affected by the proportion of fruit rejected from the fresh pack due to blemishes. Fruit size and yield data from an unpublished experiment were used to estimate returns per acre using the method of Stover et al. (2001). Data used in calculations were the following: yield = 17 tons/acre (38.1 t·ha^{-1}), mean fruit weight = 16.79 oz (476 g), SD fruit weight = 5.89 oz (167 g), and 19% of production too small to pack (added to percentage of blemished fruit to obtain total eliminations). When extrapolating to different yields it was assumed that the distribution of fruit size was unaffected by total yield, reflecting conditions where trees would have similar vigor but would vary in size. All costs for packed fruit from harvest to sale were estimated at $5.13/carton [carton = 0.8 bu (28.2 L)]. Net returns on eliminations were estimated at $0.45/carton (Muraro et al., 2002). Returns were estimated using season-long, weighted, packing-house-door averages [i.e., freight on board (FOB)] from the Citrus Administrative Committee (2002) as follows: 23 and 27 fruit/carton = $10.0; 32 fruit/carton = $8.3; 36 fruit/carton = $7.2; 40 fruit/carton = $6.7; and 48 fruit/carton = $5.5. ($1/acre = $2.47/ha; 1.0 ton/acre = 2.24 t·ha^{-1}).

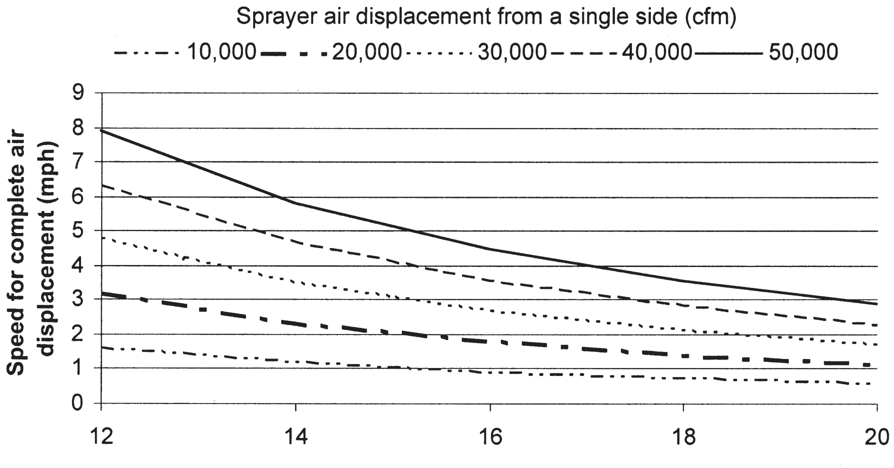

Fig. 2. Sprayer ground speed needed to achieve complete air displacement (Cromwell, 1975) in trees of different size as influenced by sprayer air displacement [10,000 to 50,000 ft^3/min (cfm) per side]. Width of trees perpendicular to rows is assumed to be similar to tree height. (1 cfm = 0.028 m^3·min^{-1}; 1 ft = 0.3 m; 1 mph = 1.6 km·h^{-1})

culled display several disorders, each of which could cause them to be excluded from fresh sales.

Incidence of windscar is greatest on exterior grapefruit, especially those from the upper exterior that are exposed to the highest wind speeds (Stover et al, 2004). In addition, the shape and texture of interior fruit tend to be most desirable for primary fresh grapefruit markets. This suggests that growers may profit from focusing on maintaining the quality of interior fruit. Unfortunately, these interior fruit are also the most difficult to spray effectively, with substantial heterogeneity in pesticide deposition (Whitney and Salyani, 1991).

Interactions of application variables and weather conditions. In most published spray experiments, conditions are selected to minimize effects of complicating variables such as wind (e.g., Carman and Jeppson, 1974). Use of lower spray volumes, with concomitant smaller droplets, is likely to be more adversely affected by difficult spray conditions than would a higher volume spray (Dibble, 1983; Fleming, 1962; Hall, 1991). Hall (2000) emphasized that effective use of low volume spraying requires greater managerial expertise, including better matching of spray equipment to trees and understanding of interactions between weather conditions and spray parameters.

Understanding limiting conditions may be key to choosing spray options

There is strong evidence that optimal efficiency/efficacy balance varies with environmental conditions, orchard conditions, equipment used, and the pest requiring control. Widespread adoption of this perspective within the industry may influence spray practices and increase profitability. The financial reasons for decreasing spray volume to the lowest level necessary are readily apparent (Table 1). By understanding the interaction between various factors influencing spray deposition and coverage, growers should be able to take advantage of increased efficiencies associated with low volume spraying, while avoiding poor pest control by only spraying low-volume under optimal conditions, and reverting to higher volume spraying when applications must be made under non-ideal conditions. A recent survey (Stover et al., 2002a), indicated that 44% of IR citrus acreage is already treated with different spray volumes at different stages in the growing season, so the concept of adapting spray practices to circumstances is already prevalent and might be readily extended.

The most useful approach to making spray options more understandable may be to identify conditions in which individual practices are most likely to compromise efficacy, efficiency, or environmental soundness of application, and provide growers with a matrix of options to guide their choices (Table 2). The complexity of this matrix may

Table 2. Matrix of spray parameters important in spraying fresh grapefruit and guidance based on wind, tree height, dew on trees, organisms to be controlled, droplet size, and foliage density.

Factor	Level	Focus issue	Selections for improved efficiency	Selections for improved efficacy	Selections for lower environmental impact	Other considerations
Wind	0–4 mph (0.0–6.4 km·h^{-1})	Efficiency and runoff	Low spray vol. 25–125 gal/acre (233.8–1169.2 L·ha^{-1})	Low spray vol. likely to be fine except large trees	Low spray vol. to reduce runoff	Night spraying most likely to provide low wind.
	4–10 mph (6.4–16.1 km·h^{-1})	Deflection of small droplets	Moderate to high spray vol. 200–500 gal/acre (1870.7–4676.8 L·ha^{-1})	Moderate to high spray vol. Do not use small capacity nozzles	Moderate to high spray vol., large nozzles to reduce drift, avoid overspray	Beware spraying last two rows downwind.
	>10 mph (>16.1 km·h^{-1}) SPRAY NOT ADVISABLE	Deflection of most droplets	High spray vol. Large trees in hedgerow are best choice if must spray	High spray vol. and large output nozzles to reduce drift and improve coverage	High spray vol., large droplets. Do not spray orchards with large gaps and avoid overspray.	If time is not an overriding factor, do not spray. Check product label for wind restrictions.
Tree ht	<10 ft (<3.0 m)	Ability of sprayer to cover whole tree	Low spray vol. and/or low profile sprayer is fine	Low spray vol. unless melanose, greasy spot or snow scales	Low spray vol. to reduce chemical runoff	Relatively easy to get good coverage.
	10–15 ft (3.0–4.6 m)		Low to moderate spray vol., tower sprayer may be best for larger trees	Mid to high spray vol., low vol. for mobile pests	Moderate to high spray vol. or low vol. with tower possibly best choice	
	15–20 ft (4.6–6.1 m)		Ideally should use a tower sprayer at any vol.	Ideally use tower sprayer at any vol. Moderate to high spray vol. for melanose, greasy spot, snowscales	Ideally should use a tower sprayer at any vol., to avoid spraying upward	May not cover top at any vol. without tower.
Dew on trees	Heavy	Runoff of spray	Low spray vol.	Low spray vol.	Low spray vol., if low wind and high humidity	If possible do not spray. Even low vol. will coalesce and run off.
	Light		Low spray vol.	Low spray vol.	Low spray vol., if low wind and high humidity	May be ideal for low vol. if low wind and high humidity
Organism to be controlled	Aphids, scab, alternaria, mites/sulfur	Location in canopy and mobility	Low spray vol.	Of little importance	Low spray vol., if low wind and high humidity	Mobile pests will encounter spray residue. Scab and alternaria are on tree periphery. Sulfur fumes provide control.
	Melanose, most scales		Low to moderate vol.	Moderate to high vol. will reduce copper marking and provide more even deposits	Moderate vol., larger droplets to reduce both runoff and drift	Lower rates of copper and avoiding copper and oil in dry & hot conditions will reduce copper marking.
	Greasy spot on fruit		Moderate spray vol.	Moderate to high spray vol.		See above. Thorough coverage is considered necessary to control fruit greasy spot with fungicides.
	Snowscale		Moderate spray vol.	High spray vol.		High vol. is often needed to reach trunk for snowscale.
Droplet size	Large	Drift, runoff, coverage and deposition	Moderate to high spray vol.	Moderate to high spray vol.	Larger droplet size results in lower long distance drift	Good choice for pests requiring good coverage, or materials that may mark fruit. High runoff but low drift potential.
	Small		Low spray vol.	Low spray vol.	Smaller droplet size results in less runoff, higher deposition, but risk of more long distance drift	Good choice for highly mobile pests, low runoff, but high drift potential, use only with low wind.
Foliage density	Thick	Distribution in interior vs. run-off	Low to moderate spray vol.	Low to moderate spray vol.	Moderate spray vol.	Slower ground speed may aid penetration.
	Moderate		Low spray vol.	Mid spray vol.	Moderate spray vol.	Moderate vol., moderate ground speed.
	Light		Low spray vol.	Moderate spray vol.	Moderate spray vol.	Higher sprayer ground speed is acceptable.

prevent widespread utilization, making this an appropriate subject for a simple expert system.

Environmental conditions. Because sprayers and tractors are expensive, most citrus production operations have only slightly more than the minimum number of sprayer units that are needed to meet their perceived needs (Indian River growers, personal communication). As a result, spray applications are made on a tight schedule and sometimes must be made when environmental conditions are not ideal.

Changing spray practices with different humidity, tree wetness, and wind speed. Small spray droplets associated with lower volume spraying are inherently subject to greater off-target drift with elevated wind speed or lower humidity (reviewed in Stover et al., 2003a). Application in the higher range of spray volumes is therefore a better choice under such conditions. In contrast, when trees are wet with dew or rain, spraying at 250–500 gal/acre is likely to greatly increase runoff in contrast to applications at 125 gal/acre or less (Hoffman and Salyani 1996). Where appropriate, standard air-blast orchard sprayers can be successfully adapted to provide a quality spray application at 125 gal/acre or even lower (Carman and Jeppson, 1974). These same sprayers can be quickly adjusted to make applications at higher spray volumes when necessary.

Night spraying. Routine spraying at night appears to be one of the greatest opportunities for both increasing efficacy of low volume sprays and reducing the potential for drift. Typically, low volume spraying results in a significant proportion of the spray being comprised of droplets smaller than 200-µm (0.008 inch) diameter, and these droplets are much more likely to be diverted from their target and drift off-site when wind speed exceeds 5 mph. Weather data from 2000 (Table 3) demonstrates the strong effect of differential air-land temperatures on wind in eastern Florida, making night time spraying very attractive. Low volume spraying is also particularly well suited to night-time applications because the presence of dew on leaves can actually aid deposition (Hoffman and Salyani, 1996). All of the IR grapefruit acreage sprayed at night was reported to receive spray volumes of 250 gal/acre or less, and half of this acreage was sprayed at very low gal/acre (Stover et al., 2002a). However, some growers avoid night spraying because of concerns about safety or increased costs of additional management for a night shift. Since most IR citrus growers have sizable operations, it appears that opportunities to save >$102/acre ($252.04/ha) per year (seven sprays at 1.5 mph and 125 gal/acre or less vs. 500 gal/acre) may justify additional investment in lighting and or managers. Growers wishing to reduce spray volume but who are compelled to spray during less calm daylight hours may balance efficiency and risk by routine use of 250 gal/acre (Salyani, 2004).

Reinforcing routine practices that need greater emphasis

SPRAYER CALIBRATION

Proper sprayer calibration is a routine requirement with obvious benefits. Applying less material than intended may compromise pest control while excessive application may increase costs needlessly while also increasing the risk of environmental contamination and phytotoxicity. Interpretation of adequate calibration practice varies widely among IR citrus growers. Many operations only recalibrate when a substantial change in the number of tanks sprayed per block is noted (Stover et al., 2002a).

Adjusting nozzle output/configuration between blocks with different spacing. Different row spacings have been used as growers have attempted to optimize orchard design. A single calibration based on the highest typical row spacing may appear to be an attractive convenience. However, when excess material use is calculated for an entire season, it is clear that this practice can be very costly (Table 4).

Minimizing overspray of trees. Because tree height is irregular in most Indian River orchards, as a result of replacing lost trees and varying soil characteristics, some degree of "overspray" is routine in most orchards, with the spray-laden air directed at the canopy and intentionally continuing somewhat above a typical tree. This overspray is considered a major contributor to off-site drift and also represents inefficient use of spray materials. Table 5 indicates the value of spray materials which may be wasted through significant overspray in several orchard scenarios. Most of the spray material that passes

Table 3. Windspeed data during spray season (1 Mar. to 30 Sept. 2000) in Ft. Pierce, Fla.

Time of day (HR)	Mean wind speed (mph)^{z}	Hours with mean windspeed (%) <5 mph	Hours with mean windspeed (%) <10 mph
2400–0400	3.6	80	99
0400–0800	3.4	81	99
0800–1200	7.5	18	78
1200–1600	9.7	1.9	56
1600–2000	7.8	10	83
2000–2400	4.3	69	99

^{z}1.0 mph = 1.61 km·h^{-1}.

Table 4. Increased annual cost of failing to recalibrate between blocks with different row spacing. The average sprayer is used to cover 250 acres (101.2 ha) per year in Indian River grapefruit with average spray material cost of $250/acre and range of $150 to $350/acre (Stover et al., 2002 a). Calculations are based on calibration for 26 ft (7.9 m) row spacing and assumes that half of the acreage sprayed per year as at the calibrated spacing and half [125 acres (50.6 ha)] at the indicated narrower row spacing.

Annual spray material cost		Distance between rows			
($/acre)	($/ha)	22 ft (6.7 m)	23 ft (7.0 m)	24 ft (7.3 m)	25 ft (7.6 m)
		Increased annual costs ($/125 acres)^{z}			
150	370.64	3408	2444	1561	749
250	617.74	5680	4074	2602	1248
350	864.84	7952	5704	3643	1747
		Excess spray material application (%)			
		18.2	13.0	8.3	4.0

^{z}\$1/125 acres = \$0.02/ha.

Table 5. Cost estimates for routine spray applications which include material sprayed above the tops of Indian River grapefruit. The average area per sprayer per year is 250 acres for Indian River grapefruit with average spray material cost of $250/acre ($617.74/ha) and range of $150 to $350/acre ($370.64 to $864.84/ha) (Stover et al., 2002a).

Tree ht (ft)[z]	Mean overspray ht (ft)	Material overspray (%)	Annual spray material cost $150/acre	$250/acre	$350/acre
			----Annual cost of materials in overspray---- ($/250 acres)[y]		
10	0.5	4.8	1786	2976	4167
	1.0	9.1	3409	5682	7955
	2.0	16.7	6250	10417	14583
15	0.5	3.2	1210	2016	2823
	1.0	6.3	2344	3906	5469
	2.0	11.8	4412	7353	10294
18	0.5	2.7	1014	1689	2365
	1.0	5.3	1974	3289	4605
	2.0	10.0	3750	6250	8750

[z] 1 ft = 0.3 m

[y] $1/250 acres = $0.01/ha.

above the target tree is not likely to contribute to pest control, with much of this material being deposited on the ground or drifting off-site (Stover et al., 2003a).

Since almost all IR orchards are bedded, there is potential for overspray of two or more ft if the sprayer nozzling is not adjusted between bed-tops and drainage furrows. A spray drift task force study (1997) reported twice as much spray moving over Florida grapefruit trees than over comparable trees in an un-bedded California orange (*Citrus sinensis*) orchard, and attributed much of this to using the same sprayer configuration on beds and furrows of the bedded Florida orchard. It should be noted that a large majority of IR growers already report either changing nozzling between beds and furrows or dedicating different sprayers to these two zones (Stover et al., 2002a).

Use of precision spray technology offers the benefit of reduced overspray and diminished spray between trees that have not formed a hedgerow. However, a recent study documented that adjustment of sprayers to each orchard by a well-trained spray operator offers substantial opportunity for additional savings, even when a typical precision spray system is used (Stover et al., 2003b).

Output variability between each side of sprayer. Significant differences between the output on the right and left manifolds of many sprayers was observed in IR sprayers even when they were outfitted with identical nozzles (Stover et al., unpublished). Of the sprayers assessed, the output of 53% were found to differ by more than 5% between the two sides, with a mean difference for all sprayers of 9.7%. Some sprayers produced output that differed by up to 30% between the two sides. These differences in output can result in substantial differences in spray applied from one row to the next, possibly affecting pest control. This source of spray variability is not apparent using most calibration methods and may warrant adoption of an annual calibration in which each side of the sprayer is tested.

Research needs. The data clearly support greater risk of spray drift when sprays with small droplets are applied with wind speed greater than 5 mph or low humidity. However, it is also well documented that application volumes greater than ~214 gal/acre (2001.7 $L\cdot ha^{-1}$) substantially increase the percentage of spray material falling from the canopy as runoff when mature citrus trees are sprayed (Cunningham and Harden, 1998). To realistically contrast environmental risks and benefits of small droplet/low volume sprays (with more drift potential) vs. larger droplet/high volume sprays (with more runoff), research data evaluating the fate of materials falling to the orchard surface is needed. This is discussed in more detail in paper II of this series (Stover et al., 2003a).

Exploring new opportunities for improved spraying

As discussed above, many improvements can be made in spray efficiency /efficacy and reduction of off-target spraying by altering management using existing orchards and sprayers. However, there are additional opportunities which can be realized when orchards are replanted or new equipment is purchased.

SPRAYER DESIGN AND SETUP

Tower sprayers. Most sprayers used in Florida citrus have a relatively low profile. Stover et al. (2003a) discussed evidence that spray application to larger trees may be enhanced by using tower sprayers that better match spray delivery to the tree architecture. A recent study supports this idea, indicating that spray penetration of Florida citrus was improved using a tower sprayer vs. a standard low-profile airblast sprayer (Koo et al., 1999). Therefore, transition to use of tower sprayers may increase spray efficacy, and practices which avoid routine upward spray discharge may decrease spray losses above the trees (Holownicki et al., 2000).

Over-row sprayers. The tunnel sprayer is another approach that may increase efficiency and reduce offsite deposition, but is not currently used in IR citrus. Such sprayers are used only on short trees or vines, since the sprayer must surround the top and both sides of the row during operation, applying materials to both sides at the same time. This semi-contained spray procedure greatly reduces the amount of downwind drift and permits high speed (5 mph) application in apples (*Malus* x*domestica*)with no negative effect on canopy deposition (Peterson and Hogmire, 1995). However this technology would only be practical for high density plantings where tree size is rigorously controlled. While tunnel sprayers reduce drift, some designs increase ground deposition under the canopy compared to conventional air blast sprayers, but this might be alleviated by inclusion of a system for recovery of spray deposited within the tunnel (Peterson and Hogmire, 1995).

Air induction nozzles. The air induction (AI) nozzle was designed to reduce drift associated with small droplet size and low-volume applications. As spray fluid is emitted, these venturi-type nozzles incorporate air into the droplets to increase droplet size and reduce drift potential. Field crop pest and weed control have been the subject of most studies using air induction nozzles. In these studies, drift was reduced when AI nozzles were compared to conventional nozzles (Derksen et al., 1999; Klein and Johnson, 2002), and spray efficacy was similar (Klein and Johnson, 2002) or somewhat reduced (Etheridge et al., 1999). Several reported orchard spray experiments were conducted with AI nozzles and all indicate that there was no significant difference in pest control efficacy between sprays made with conventional nozzles and air-induction nozzles (Cross et al., 2002; Heinkel et al., 2000). These studies were conducted with deciduous fruit trees which tend to have less dense canopies than citrus and spray applications were compared at volumes much lower [~22 gal/acre (205.8 $L \cdot ha^{-1}$)] than those routinely used in mature grapefruit. Studies with AI nozzles in grapefruit are needed to compare conventional hollow cone and AI nozzles at low vs. moderate water volumes.

ORCHARD AND TREE CHARACTERISTICS

Dwarf trees. Growers with larger trees typically use higher spray volumes (Stover et al., 2002a), with much of this spray directed upward to reach tree tops. There is general consensus that spraying efficiency can be increased by developing higher density orchards with smaller trees (Hall, 1991; Morgan, 1983). Use of small trees would also likely increase spray efficacy by reducing both canopy width and distance from the sprayer to the most-distant target surfaces, thus matching the typical low profile sprayer output more closely with canopy geometry. Minimizing upward spraying may reduce movement of materials over trees (e.g. Holownicki et al., 2000). In recent years, several Florida growers have experimented with closer plantings of smaller trees (Brown, 1999). New size-controlling rootstocks (Grosser et al., 1998) may further enhance this trend.

Non-orchard buffer areas. An obvious method for reducing off-site contamination is to place obstacles and/or greater distance between the sprayer and the area to be protected. Buffer area plantings should be selected based on several characteristics. Plants must require little care and should not harbor citrus pests. Species should be horizontally compact or tolerant of pruning, so that roots and shoots do not compete with citrus trees for light water, nutrients, etc.

A windbreak is a buffer planting which is tall enough to significantly intercept spray droplets and reduce wind velocities, allowing settlement of droplets within the orchard confines. It is anticipated that an effective windbreak should reduce off-site drift by more than 50% (Richardson et al., 2002). Windbreaks and shelterbelts are mandated for fruit growers in the Netherlands and are reported to reduce drift by as much as 90% (Porskamp et al., 1994, cited in Hall, 2000). Ucar and Hall (2001) caution that complex air flow near windbreaks can make it difficult to optimize design. Effective windbreak species should allow some air to pass through them while they filter droplets out of the airstream. Fine evergreen foliage is reported to be 2–4 times more effective in removing spray droplets than broadleaf species (Ucar and Hall, 2001). However, vegetation with a very thick canopy may increase the vertical movement of droplets over the trees, thus increasing drift (reviewed in Ucar and Hall, 2001). It may be necessary to include the windbreak plantings in scouting activities since they may serve as hosts for some pests. In some cases, it may be necessary to spray the windbreaks. Windbreaks do not need to be restricted to field edges. Lower growing plants can be used to intercept spray drift along numerous in-field drainage ditches and canals in IR citrus orchards. In addition to reducing off-site pesticide movement, windbreaks may provide the additional advantages of reducing wind damage to fruit (Freeman, 1976), slowing the progress of wind-blown disease inoculum (Gottwald and Timmer, 1995), and providing protection in advective freeze events (Davies and Albrigo, 1994).

Orchard perimeters as a buffer. Drift may also be reduced by altering spraying practices or orchard design. Significant amounts of applied pesticides may be blown through several rows of trees when using airblast sprayers. Studies show that the majority of off orchard drift (up to 70%) comes from spraying the last two downwind rows (Fox et al., 1993; Salyani, 1995) and that with spray volumes ranging from 72–544 gal/acre (673.5–5088.4 $L \cdot ha^{-1}$), ground deposits declined dramatically after 50 ft (15.2 m) (Salyani, 1995; Spray Drift Task Force, 1997). In fact, spraying both sides of the outer 4–5 rows of some trees has been estimated to be responsible for up to 90% of off-site drift (Society of Environmental Toxicology and Chemistry, 1994). Buffer zones with windbreaks or a 50-ft open space could greatly reduce off-site deposition. Spraying only inward on the outer rows is a similar but less drastic approach.

Ditch management to enhance retention and decomposition of pesticides. Plants present in drainage ditches, flow-ways, and storage areas can significantly reduce pesticide loadings. This reduction is due to adsorption of the pesticides onto root and leaf surfaces, as well as absorption into the plants. In general, as the water solubility of pesticides decreases, adsorption/absorption by plants tends to increase (Trapp and McFarlane, 1995). Considerable research has been conducted showing that plants are capable of removing and bio-transforming organic pesticides in the water column (e.g. Wilson et al., 2000; Wilson et al., 2001). Procedures to manage aquatic weeds for optimal pesticide remediation should be investigated and used to develop sound recommendations.

IMPROVED SPRAY MATERIALS

Effects of surfactants and emulsifiers. Spray adjuvants can substantially influence drift and understanding their effects may offer opportunities for improving spray performance. In wind-tunnel studies using small droplets [volume median diameter (VMD) of 159 μm (0.006 inch), without surfactant], inclusion of surfactants has increased drift as much as 2 fold with some nozzles types, but the least effect on drift was observed with hollow cone nozzles typical of orchard sprayers (Butler-Ellis and Bradley, 2002). Inclusion of 0.5% emulsion concentrate markedly reduced spray drift and had the greatest effect with the hollow cone nozzles, reducing drift up to 23 ft (7.0 m) or 4 fold. The effect of such drift-reducing adjuvants on spray efficacy should be assessed more thoroughly before they can be recommended for standard use.

An alternative concept is to increase effectiveness of larger, less drift-prone, droplets [VMD of 200–300 μm (0.008–0.012 inch)] by inclusion of an appropriate spreader/sticker to reduce bouncing off foliage (Reichard et al., 1998; Stevens et al., 1993). This may need to be combined with use of air induction nozzles since conventional hollow cone nozzles produce a broad spectrum of droplets including some that are small and drift-prone. Again, research is needed to verify that such spray practices do not compromise efficacy.

Materials with longer residual activity. Identifying new materials or improved formulations with greater residual activity could greatly increase material effectiveness and might reduce potential environmental impact. Unfortunately, development of pesticides is costly and time consuming. New formulations of copper hydroxide have just been released that are reported to have markedly improved rainfastness (Griffin LLC, personal communication).

INFORMATION SYSTEMS TO IMPROVE MANAGEMENT

An expert system for agriculture is a decision-making tool based on a variety of environmental and crop-related inputs. Expert systems have been proposed and developed for many years, but have not been readily adopted and used. Increasing grower familiarity with computers and availability of inexpensive and reliable weather loggers have greatly increased the usefulness and effectiveness of expert systems and other tools for information management. The following describes two such systems, but it is likely that computer models and data management will soon support most aspects of crop production.

Expert system for determination of need for copper application. Rapid fruit growth and abundant rainfall during the prolonged period in which fruit are susceptible to melanose make control of this disease a great challenge for IR grapefruit growers. Melanose is therefore the target of most sprays applied to IR grapefruit and yet significant amounts of fruit continue to be unacceptable for fresh sales as a result of melanose blemishes. Current recommendations and standard practice for fresh IR grapefruit are that spraying of copper (Cu) fungicides, at ~2 lb/acre (2.2 kg·ha^{-1}) metallic Cu, begins when fruit are 0.25–0.5 inch (0.64–1.27 cm)in diameter and continues at 3-week intervals until fruit reach 2.5–3.0 inches (6.35–7.62 cm) in diameter (Timmer et al., 2003).

In an effort to develop a more effective system for scheduling melanose sprays, an expert-system was developed to model average Cu levels on the fruit (Lin et al., 1999). Initial Cu deposits are estimated based on the concentration of copper in the spray and gallons applied per acre. Effects of fruit growth and rainfall are used to estimate decline in average Cu residues and growers are advised to reapply Cu fungicides when the predicted micrograms per unit surface area approaches a level that would permit melanose spore germination and resulting infection. The premise of this approach is that reliance on a calendar-based spray program will sometimes result in fruit unprotected by Cu residues after periods of heavy rainfall, and will sometimes result in applications when residues are already adequate, such as when little rainfall has occurred. This approach offers considerable promise for greater melanose control efficacy and more efficient use of Cu fungicides, and is being tested in field trials.

Intensive monitoring for pests at critical threshold levels. The goal of most control programs should be to maintain damage at an acceptable level, rather than to completely eradicate a pest species. In the past, to successfully and efficiently manage pest species at acceptable levels, managers needed a thorough knowledge of both pest biology and the dynamics of population change. A coordinated citrus rust mite scouting and expert recommendation system has been in place since 1997, under the name of Entonet (Burchfield, 2001). Entonet uses a straightforward scouting system in which orchard data are entered directly into personal digital assistants (PDAs, Palm Pilots) and are then downloaded to the individual grower's computer and confidentially shared with a base of all Entonet users. The program recommends appropriate rust mite control measures based on projected weather, stage of crop development, and region-wide rust mite population dynamics.

Where do we go from here?

Analyses suggest that IR spray practices vary significantly (Stover et al., 2002a). Much of this variability may result because practices were not developed using a systematic science-based approach. Therefore, there are substantial opportunities to improve practices using both existing information (Stover et al., 2003a) and by identifying and pursuing the most critical research needs. Increasingly, citrus production managers are required to make more complex decisions, and make these decisions quickly and efficiently. While citrus producers are concerned about environmental issues, the pressure of making a profit in their business makes it unlikely that environmental concerns will be paramount in their choices. The substantial opportunities for improving spray efficiency and efficacy, and the associated potential savings, should provide a strong incentive for growers to reevaluate their spray practices. It is incumbent on the extension community to develop and deliver educational programs which provide relevant guidance while also incorporating strong elements of greater environmental awareness.

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