Evaluation of two organosilicone adjuvants at reduced foliar spray volumes in South African citrus orchards of different canopy densities

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A B S T R A C T


Citrus producers in South Africa generally use high spray volumes (6000 to 16,000 l ha⁻¹) to control pests and diseases adequately for the fresh fruit market. In order to study the benefit of organosilicone adjuvants at reduced spray volumes, trials were conducted with two organo tri-siloxane adjuvants. Two separate spray trials were conducted in the Western and Eastern Cape provinces of South Africa in uniform navel orange orchards. Break-Thru S240 (super-spreader) and Break-Thru Union (spreader-sticker), at recommended dosages per hectare (300 ml ha⁻¹, respectively), were sprayed separately in combination with a yellow fluorescent pigment (1 ml l⁻¹) at a high (20 l tree⁻¹ = 9600 to 12,100 l ha⁻¹, depending on tree and inter-row spacing), medium (14 l tree⁻¹ = 6500 to 8500 l ha⁻¹) and low (8 l tree⁻¹ = 3700 to 4800 l ha⁻¹) spray application volumes. Sprays consisting of the fluorescent pigment in water alone were used as control treatments. Trees were sprayed from both sides with a commercial multi-fan tower sprayer (BSF-Multiwing) at a constant tractor speed (2.4 km h⁻¹) and spray pressure (1500 kPa). The different spray volumes were achieved by using different spray nozzles (TeeJet Disc-Core type; full and hollow cone nozzles D3-DC56/46, D4-DC56/46, D5-DC56/46). Leaves were sampled from six canopy positions (inner and outer canopy position at bottom, middle and top of the tree). Deposition quantity and quality of fluorescent pigment were determined on upper and lower leaf surfaces using fluorometry, digital photomacrography and image analyses. Spray uniformity and efficiency were also compared among treatments. Deposition quantity generally increased with increasing spray volume, but normalised values showed better spray efficiency at lower volumes. In pruned and less dense canopies, a beneficial effect of adjuvants was observed in terms of deposition quantity, efficiency and uniformity, especially at reduced volume applications (14 l tree⁻¹) on the inside and outside of the canopy. Little improvement in deposition quality was generally observed with the use of adjuvants. These benefits were not as evident in very dense canopies, illustrating the importance of canopy management when spraying at reduced volumes. Data obtained from the study is valuable for future improvement in spray application methodology in South Africa and other developing countries.

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1. Introduction

South African citrus fruit producers rely heavily on medium to high volume fungicide spray applications (Grout, 1997, 2003) to protect citrus fruit from challenging diseases such as Citrus black spot (CBS) (Phyllosticta citricarpa (McAlpine) van der Aa (syn. Guignardia citricarpa Kiely)) (Kotze, 1981, 2000; Schutte et al., 1997) and Alternaria brown spot (Alternaria alternata (Fr. Fr) Keissl., tangerine pathotype) (Schutte, 1996).
Citrus trees in South Africa are generally large and dense, with size depending on cultivar, rootstock, planting density and climatic region. Tree geometry and density complicates adequate deposition of fungicide or insecticide sprays on outer and the difficult-to-reach inner canopy susceptible leaves and fruit (Cunningham and Harden, 1998, 1999; Hoffmann and Salyani, 1996; Farooq and Fourie, 2006). Effective deposition of the active ingredient on target surfaces (leaves, twigs and fruit) is needed for effective disease control since disease control and spray deposition are closely related (Holownicki et al., 2002; Van Zyl et al., 2013). Hence medium to high volume fungicide spray applications ranging from 6000 to 16,000 l ha\(^{-1}\) (with 8000 l ha\(^{-1}\) being the norm) (Grout, 1997, 2003), which is almost double or triple the volumes used in other citrus producing counties such as Spain (Vicent et al., 2009) and Florida in the United States of America (Dewdney and Timmer, 2012). These application volumes do provide an acceptable balance between efficacy and efficiency based on existing economic considerations, especially considering the emphasis placed on effective CBS control given its quarantine status in certain export markets (EPPO, 2014). Most importantly, it serves as a “buffer” for loss of efficacy due to calibration and operator error and the use of inadequate spray machinery, equipment and technique. However, these high spray volumes are super-optimal, costly and not efficient in terms of time and input costs. Deposition is also not optimally efficient due to spray run-off and erosion and drift (Salyani and Farooq, 2004; Fourie et al., 2009; Cunha et al., 2012; Schutte et al., 2012). Off-target deposition of fungicides is increased at these excessively high spray volumes (8000 l ha\(^{-1}\) and higher) (van Zyl and Fourie, unpublished results), which in turn is an economical and an environmental pollution problem (De Jong et al., 2008; Furness et al., 2006a,b; Salyani and Farooq, 2004; Stover et al., 2002; Cunha et al., 2012). Reduced volume sprays have the potential to reduce the economic and environmental impact/cost of fungal disease control and to be more effective (Cunningham and Harden, 1998, 1999).

Adjuvants can be used to potentially reduce spray volumes and as a result reduce application time and input costs and improve deposition parameters and disease control (Butler Ellis and Tuck, 1999; Green and Beestman, 2007; Gaskin et al., 2004; Gent et al., 2003; van Zyl et al., 2010a,b). Organomodified trisiloxanes or organosilicones as tank mix adjuvants are non-ionic surfactants that dramatically reduce surface tension and/or modify surface characteristics of hydrophobic leaves and/or fruit thereby improving wetting, spreading and dispersing effect of the sprayed mixture on the surface or interface (Hazen, 2000). The interaction between adjuvant concentration and spray volume and to some extent the effect it has on the biological efficacy of certain crop protection products (Greyson et al., 1995, 1996) has been studied on fruit (Stevens, 1993), easy to wet foliage of potatoes (Greyson et al., 2006) and on difficult to wet foliage of wheat (Gaskin and Murray, 1997; Greyson et al., 1996). In all cases, depending on the surface characteristics of the sprayed target, it was found that increased concentration of adjuvant or organosilicone at increased spray volumes led to increased spray run-off and reduced retention, whereas, increased concentration of organosilicone and decreased spray volume had the opposite effect (De Ruiter et al., 1990; Gaskin and Murray, 1997; Stevens et al., 1993). This interaction and its results are likely to influence the biological efficacy of crop protection products deposited.

In South Africa, these types of adjuvants are regularly used with fungicide and pesticide application, yet little literature exists on the effect of adjuvants, specifically organo tri-siloxane adjuvants, at different application volumes in citrus canopies. Therefore, the objectives of this study were to evaluate the influence of two organo tri-siloxane surfactants at reduced application volumes in South African citrus orchards on different deposition parameters. In previous studies, an spray deposition assessment protocol, consisting of fluorometry, digital photomacography and image analysis, was developed and improved (Brink et al., 2004, 2006; Fourie et al., 2009; van Zyl et al., 2010a,b, 2013) and was recently used to effectively determine the deposition quantity (the amount of active ingredient landed and retained on a target surface) and persistence (amount of product retained over time) of copper fungicides on orange leaves and fruit (Schutte et al., 2012). Recent improvements to the spray deposition assessment protocol also allows for determining deposition quality (uniformity of active ingredient distribution on the target surface) (J.G. van Zyl; unpublished results). This deposition assessment protocol was used in this study.

2. Materials and methods

2.1. Spray application

2.1.1. Field evaluation

The first trial (Dense canopy trial) was conducted in uniform (areas where trees have similar canopy characteristics e.g. height, width and density) sections of a 14-year-old ‘Bahiana Araras’ navel (Citrus sinensis (L.) Osbeck) orchard on the farm Die Vlei (Clanwilliam, Western Cape, South Africa) in February 2012. Trees were large (3.7 \times 3.4 m tree \times W (height \times width or depth across row)) and planted at a 3 \times 5.5 m tree and inter-row spacing. Canopy density was visually determined on a 5-point scale (1 – very sparse leaf concentration, heavily aerated; 2 – sparse leaf volume, well aerated; 3 – good balance between leaf volume and canopy aeration; 4 – dense canopy, sparsely aerated; 5 – very dense leaf concentration, poorly aerated with no pruned canopy windows, i.e. unmanaged) and was rated to have a density of 4.5. Sprays were applied early morning as soon as trees were dry from dew. Air movement (wind speed at m s\(^{-1}\)) inside the orchard row was 1.8 m s\(^{-1}\) with air temperature and relative humidity being 26 °C and 18%, respectively. For each treatment combination, a single row-section of 10 trees was marked and sprayed from both sides with a tractor-drawn, power take-off (PTO) powered, air-blast BSF-Multiwing sprayer (BSF, Hoedspruit, South Africa). The spray applicator is a high profile sprayer with 22 nozzle ports per side, with air being generated by five fans per side positioned vertically behind the nozzles without ducting on the sprayer tower, to match canopy height. A high profile sprayer was used to negate the effects of using low profile applicators in large canopies (Cunningham and Harden, 1998; van Zyl and Fourie, unpublished results). Spray volume was standardised to 1 l tree\(^{-1}\) since inter-row spacing differed between the two trials sprayed. Even though spray volume differed between trials, the volume per tree was similar. Sprays consisted of three separate treatments, each at a high (20 l tree\(^{-1}\) = 12,273 l ha\(^{-1}\)), medium (14 l tree\(^{-1}\) = 8273 l ha\(^{-1}\)) and low (8 l tree\(^{-1}\) = 4727 l ha\(^{-1}\)) spray volume. The three separate treatments contained a yellow fluorescent pigment (40% EC (SARDI, Loxton, South Australia) at 1 ml l\(^{-1}\)) alone (no adjuvant added control treatment), yellow fluorescent pigment (1 ml l\(^{-1}\)) together with adjuvant Break-Thru S240 [(Evonik Degussa Africa, Midrand, South Africa) at 300 ml ha\(^{-1}\)] and yellow fluorescent pigment (1 ml l\(^{-1}\)) together with Break-Thru Union [(Evonik Degussa Africa, Midrand, South Africa) at 300 ml ha\(^{-1}\)]. Break-Thru S240 is a superspreader, trisiloxane-based adjuvant that enables extremely low surface tension of aqueous solutions whilst causing superspreading of droplets due to droplet size increase. Break-Thru UNION is a spreader-sticker trisiloxane-based adjuvant that increases wetting and adhesion on target surfaces and reduces drift potential due to large increase in droplet size. Tractor speed, PTO speed and spray pressure was kept constant at 2.4 km h\(^{-1}\),
540 rpm and 1500 kPa, respectively, with spray volume being manipulated by using different spray nozzles (Teejet Disc-Core type full and hollow cone nozzles: Low – D3-DC56/46, medium – D4-DC56/46, High – D5-DC56/46). Two buffer rows of trees were left unsprayed between treatment blocks. The spray tank, spray nozzles, filter and pipes of the spray machine were thoroughly washed and flushed after each treatment.

The second trial (Open canopy trial) was sprayed in uniform sections of a well-pruned ‘Palmer’ navel (C. sinensis (L.) Osbeck) [3.65 × 3.2 m trees (H × W) orchard with a canopy density of 2.5 on a 5-point scale; 3 × 7 m tree and inter-row spacing] orchard on the farm Sun Orange Farms (Addo, Eastern Cape, South Africa) in April 2012. Spray application was conducted early morning with in-row air movement measured at 2 m s⁻¹. Temperature during application was 22 °C and relative humidity 34%. Apart from the tree canopies being well aerated (less dense), the methodology used was exactly the same as the first trial. Spray volumes pre tree was the same as the first trial at high (20 l tree⁻¹), medium (14 l tree⁻¹) and low (8 l tree⁻¹) volume applications, but realised lower per hectare rates (9643 l ha⁻¹, 6500 l ha⁻¹ and 3714 l ha⁻¹, respectively) at the wider inter-row spacing (7 m).

2.1.2. Sampling of field evaluations
As replications, three random uniform trees were selected from each sprayed section (treatment) from which leaves were sampled for spray deposition analysis. After the spray mixture had dried, twelve randomly selected intact leaves were carefully sampled from each of the various positions in the tree canopy; inner (>30–50 cm into the tree) and outer canopy (leaves on the outside of the tree) at the top, middle and bottom sections of each of the selected trees (72 leaves per replication). Leaves picked from these six positions were collected and stored separately in marked polyethylene sandwich bags. Stored leaves were transported back under cool, dry conditions to the laboratory where they were stored at 4 °C until further analysis.

2.2. Spray deposition analysis
For deposition analysis, petioles were removed from leaves using a pair of scissors at the base of the leaf blade. A single leaf was positioned in the middle of a back-illuminated red Perspex box (300 × 210 × 110 mm) inside a dark room to reduce any shadowing and to enhance edging of leaves in captured images during analysis. The leaf was covered with a glass pane (200 × 200 × 2 mm) and illuminated using an ultra-violet light source (UV-A; ≈ 365 nm; Labino Mid-Light; www.labino.com). Digital photos were taken in Canon RAW file format (.CR2 ≈ 10 MB) of the adaxial and abaxial leaf surfaces using a Canon EOS 40D camera equipped with a 60 mm macro lens. The camera was attached to a tripod in a fixed position directly above the leaf. RAW image files were converted to 8-bit Exif-TIFF (.TIF ≈ 30 MB) with Digital Photo Professional version 3.1.0.0 (CANON INC.; www.canon.com) files for digital image analysis to determine the deposition parameters (Van Zyl et al., 2013).

Spray deposition assessment involved digital image analysis with Image Pro Plus software version 7.0 (Media Cybernetics, www.mediacy.com) to determine the deposition quantity and quality per leaf. Similar to the methodology used in Van Zyl et al. (2013), deposition quantity was measured as percent total leaf area covered by pigment particles (percentage fluorescent particle coverage; FPC%) (Van Zyl et al., 2013). For the deposition quality assessment, the leaf area was divided into equally-sized squares [100 × 100 pixels (10,000 pixels)]. Depending on the leaf size, this amounted to as few as 20 to more than 250 individual squares per leaf, of which the percent area covered by fluorescent pigment particle was determined for each square. The Interquartile Coefficient of Dispersion (ICD%), a form of the Coefficient of Quartile Variation (CQV) (Bonnet, 2006), per leaf [(3rd quartile – 1st quartile)/(3rd quartile + 1st quartile)]*100] was used as a measure of deposition quality per leaf, i.e. uniformity of deposition on the leaf surface. Low interquartile coefficient of dispersion values was indicative of better deposition quality. This analysis method is an improvement on previously used methodology (Van Zyl et al., 2013). Deposition uniformity between leaves was calculated as the CV% in pigment deposition in a 12 leaf batch (Standard Deviation × 100/mean) and deposition efficiency was expressed as deposition quantity normalised to FPC% per l tree⁻¹.

2.3. Benchmarking
Deposition data were subjected to the FPC benchmark model developed by Van Zyl et al. (2013) to evaluate the effectiveness of deposition in relation to theoretical disease control that can be achieved on foliage. The FPC50 (2.07 FPC%) and FPC75 (4.14 FPC%) benchmarks indicate 50% and 75% theoretical control of Alternaria Brown Spot on mandarin leaves, respectively.

2.4. Statistical analysis
A completely random split plot design with treatment as main plot factor, position within each tree canopy as subplot factor and leaf surface (upper/lower) as sub-subplot factor was used. Deposition quantity (FPC%), quality (ICD%), uniformity (CV%) and efficiency (FPC% per l tree⁻¹) data were subjected to appropriate analysis of variance (ANOVA). Fisher’s LSD was calculated to identify significant differences between treatments at a confidence interval of 95%. Data from upper and lower leaf surfaces were analysed separately, but were combined when describing the results. Data was also subjected to regression analysis and Pearson’s correlation to demonstrate the possible relations between deposition quantity, quality and uniformity measurements. SAS version 8.2 statistical software (SAS institute Inc., 1999) was used for analysis.

3. Results
Analysis of variance indicated significant interactions between trials. These differences between trials were largely ascribed to canopy density and the trials were therefore analysed separately. Unless significant higher order interactions were observed from the analysis of variance, the 2-factor treatment × volume and treatment × horizontal canopy position interactions were discussed to simplify interpretation of subtle treatment effects.

3.1. Dense canopy trial – ‘Bahianina Araras’ navel orchard (Clanwilliam, Western Cape)

3.1.1. Deposition quantity
Analysis of variance of deposition quantity (FPC%) indicated no significant interactions (P < 0.05), but some significant main effects: vertical canopy position (P < 0.0001), horizontal canopy position (P = 0.0015) and spray volume (P = 0.0078). A somewhat lower, but yet arguably meaningful effect was also observed for treatment effects (P = 0.0756).

For vertical canopy position, the highest deposition was realised at the top of the tree (62.2 FPC%) which differed significantly from that at the bottom (47.9 FPC%) and the middle of the tree (45.7 FPC%), which did not differ significantly from each other.

Evaluation of the treatment × volume interaction (P = 0.531), indicated that the control treatment of water only (7.28 FPC%) and
the Break-Thru S240 treatment (7.49 FPC%) retained the highest amount of pigment on leaves at 20 l tree⁻¹, statistically more than that retained by all other treatments. Pigment retained by Break-Thru Union at 20 l tree⁻¹ (5.85 FPC%) and 14 l tree⁻¹ (5.05 FPC%) was statistically lower than that of above mentioned treatments and did not differ significantly from the amount retained on leaves by water only at 14 l tree⁻¹ (5.82 FPC%). The lowest amount of pigment was retained by Break-Thru Union at 8 l tree⁻¹ (3.46 FPC%) (Table 1).

For horizontal canopy position, treatments generally deposited higher deposition quantities on the outside of the tree (5.65 FPC%) in relation to the inside of the tree (4.72 FPC%) over all treatments. There was no significant interaction for treatment x horizontal canopy position (P = 0.532). For water and Break-Thru S240, deposition quantities on outer and inner canopy leaves were not significantly different, but inner canopy deposition was significantly lower for Break-Thru Union (Table 2).

### 3.1.2. Deposition uniformity

Analysis of variance of deposition uniformity between leaves (in a 12-leaf batch) indicated a significant interaction for treatment x vertical canopy position (P = 0.0251) and a significant effect for horizontal canopy position (P = 0.0501). The treatment x volume interaction, although not significant (P = 0.6676), was discussed for better interpretation of the data. Break-Thru Union at 8 l tree⁻¹ improved deposition uniformity (58.47 CV%) in relation to water only (68.07 CV%) and S240 (67.54 CV%) treatments. Although not statistically significant, this marginal effect might prove meaningful under field conditions and should be researched further. This marginal effect was also observed at 20 l tree⁻¹, but not at 14 l tree⁻¹ (Table 1).

For the significant interaction treatment x vertical canopy position, the least variation in deposition uniformity was realised by water only treatment (52.63 CV%) in the bottom of the canopy whilst the highest variation in deposition between leaves were realised by water only in the top of the canopy (67.39 CV%), differing statistically from that of the lowest variation. Deposition uniformity realised by adjuvant treatments did not improve at different canopy positions in relation to the control treatment (results not shown).

Adjuvant treatments did not improve deposition uniformity significantly on the inside or outside of the canopy in relation to the control treatment (57.93 and 62.39 CV%, respectively) (Table 1).

### 3.1.3. Deposition efficiency

Analysis of variance of deposition efficiency [normalised deposition FPC% to a spray volume of 1 l tree⁻¹] indicated no significant interactions (P > 0.05), but some significant main effects: vertical canopy position (P < 0.0001) and for horizontal canopy position (P < 0.0001). A meaningful effect was also observed for treatment effects (P = 0.0582).

The interaction treatment x volume (P = 0.237) and treatment x horizontal canopy position (P = 0.267) was evaluated for deposition efficiency. At 8 l tree⁻¹, the water only treatment (0.51 FPC% per l tree⁻¹) realised the best deposition efficiency, and Break-Thru S240 (0.45 FPC% per l tree⁻¹) and Union (0.43 FPC% per l tree⁻¹) realised similar deposition efficiency at the same volume. At 14 l tree⁻¹, Break-Thru S240 (0.37 FPC% per l tree⁻¹) and water only (0.36 FPC% per l tree⁻¹) realised the best deposition efficiency, but not differing statistically from the markedly lower deposition efficiency realised by Break-Thru Union (0.29 FPC% per l tree⁻¹). At 20 l tree⁻¹, deposition efficiency following water only (0.42 FPC% per l tree⁻¹) sprays was significantly better than that of Break-Thru S240

### Table 1

Mean deposition quantity, uniformity, efficiency and quality realised by the water only control treatment (Water) and adjuvant treatments Break-Thru S240 (S240) and Break-Thru Union (Union) on leaves following sprays at 8, 14 and 20 l tree⁻¹ to dense canopies in a Bahianina Araras' navel orchard (trial 1).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Deposition quantity (FPC%)</th>
<th>Deposition efficiency (FPC% normalised l tree⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 l tree⁻¹</td>
<td>14 l tree⁻¹</td>
</tr>
<tr>
<td>Water</td>
<td>4.06 cd</td>
<td>5.82 b</td>
</tr>
<tr>
<td>S240</td>
<td>3.61 d</td>
<td>4.09 cd</td>
</tr>
<tr>
<td>Union</td>
<td>3.46 d</td>
<td>5.05 bc</td>
</tr>
</tbody>
</table>

Deposition quantity (CV% between leaves)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Deposition quality (ICD%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>51.58 d</td>
</tr>
<tr>
<td>S240</td>
<td>56.40 ab</td>
</tr>
<tr>
<td>Union</td>
<td>54.12 bcd</td>
</tr>
</tbody>
</table>

*For each parameter separately, values in each group of three columns for one variable followed by the same letter do not differ significantly (P > 0.05) according to Fisher’s least significant difference test.

### Table 2

Mean deposition quantity, uniformity, efficiency and quality realised by the water only control treatment (Water) and adjuvant treatments Break-Thru S240 (S240) and Break-Thru Union (Union) on leaves on the inside and outside of the dense tree canopies in a Bahianina Araras' navel orchard (trial 1).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Deposition quantity (FPC%)</th>
<th>Deposition efficiency (FPC% normalised l tree⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outer canopy</td>
<td>Inner canopy</td>
</tr>
<tr>
<td>Water</td>
<td>6.10 a</td>
<td>5.35 ab</td>
</tr>
<tr>
<td>S240</td>
<td>5.39 ab</td>
<td>4.74 bc</td>
</tr>
<tr>
<td>Union</td>
<td>5.48 ab</td>
<td>4.07 c</td>
</tr>
</tbody>
</table>

Deposition uniformity (CV% between leaves)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Deposition quality (ICD%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>53.31 bc</td>
</tr>
<tr>
<td>S240</td>
<td>57.37 a</td>
</tr>
<tr>
<td>Union</td>
<td>57.45 a</td>
</tr>
</tbody>
</table>
(0.29 FPC% per l tree\(^{-1}\)), but similar to Break-Thru Union (0.36 FPC% per l tree\(^{-1}\)) (Table 1). On outer canopy leaves, adjuvant treatments realised less deposition efficiency, although not significantly less than the water only control treatment on the outer canopy. However, on inner canopy leaves, water only (0.40 FPC% per l tree\(^{-1}\)) realised statistically better deposition efficiency than that of the adjuvant treatments (S240 = 0.33 FPC% per l tree\(^{-1}\) and Union – 0.29 FPC% per l tree\(^{-1}\)) (Table 2).

3.1.4. Deposition quality

Analysis of variance of deposition quality (ICD%) indicated significant interactions for treatment × volume (\(P = 0.0331\)) and a meaningful interaction for treatment × horizontal canopy position (\(P = 0.0633\)). The least variation in pigment distribution was realised by the water-only treatment applied at 8 l tree\(^{-1}\) (51.58 ICD%), significantly better than S240 (56.4 ICD%) and markedly better than Union (54.12 ICD%) at this spray volume. This was also the case at 14 l tree\(^{-1}\) (52.32 ICD%); significantly better than Union (59.16 ICD%) and marginally better than S240 (55.82 ICD%). Statistically similar deposition quality levels (52.45–56.37 ICD%) were realised between treatments at 20 l tree\(^{-1}\), with Break-Thru S240 (52.45 ICD%) realising the lowest variation in pigment distribution (Table 1).

Evaluating the interaction treatment × horizontal canopy position, overall better deposition quality was realised by Break-Thru S240 and Union on inner canopy leaves (52.42 and 55.63 ICD%, respectively), marginally better than on outer canopy leaves (57.37 and 57.4 ICD%, respectively). However, sprays with water only realised better deposition quality on the inner (52.65 ICD%) and outer canopy leaves (53.31 ICD%) (Table 2).

3.1.5. Benchmarking

Deposition quantity results for the treatment × volume × horizontal canopy position interaction were compared to the FPC benchmarks (Van Zyl et al., 2013). All treatments at 8, 14 and 20 l tree\(^{-1}\) obtained deposition quantity levels sufficiently above the FPC\(_{50}\) and FPC\(_{75}\) benchmarks on the outside of the canopy, indicating sufficient deposition quantity for control above 75%. However, on the inside of the canopy, all treatments at 8 l tree\(^{-1}\) realised deposition quantities above the FPC\(_{50}\) but below the FPC\(_{75}\) benchmarks. At 14 l tree\(^{-1}\), the water only treatment and Break-Thru Union deposited quantities above the FPC\(_{75}\) benchmark. At 20 l tree\(^{-1}\), deposition realised by the control treatment and adjuvants were sufficiently above the FPC\(_{75}\) benchmark (Fig. 1).

3.2. Open canopy trial – ‘Palmer’ navel orchard (Addo, Eastern Cape)

3.2.1. Deposition quantity

Analysis of variance of deposition quantity (FPC%) indicated a significant interaction for treatment × volume (\(P = 0.0047\)) and no significant interaction for treatment × horizontal canopy position (\(P = 0.218\)).

At 8 l tree\(^{-1}\), Break-Thru Union (4.66 FPC%) realised markedly, but not significantly, higher deposition quantity than the water only (3.59 FPC%) and Break-Thru S240 (3.73 FPC%) treatments. At 14 l tree\(^{-1}\), the adjuvants resulted in similar deposition quantities (5.84–5.85 FPC%), significantly higher than the water only control treatment (3.42 FPC%). At 20 l tree\(^{-1}\), Break-Thru Union (7.17 FPC%) realised significantly higher deposition quantity than water only (5.45 FPC%) and Break-Thru S240 (4.54 FPC%) (Table 3).

For the treatment × horizontal canopy position interaction, Break-Thru Union realised significantly higher deposition quantity on outer canopy leaves (6.39 FPC%) than Break-Thru S240 (4.78 FPC%) and water only (4.63%). On inner canopy leaves, adjuvant treatments Break-Thru Union (5.40 FPC%) and S240 (4.54 FPC%) realised significantly higher deposition quantities than water only treatment; Union significantly better than S240 (Table 4).

3.2.2. Deposition uniformity

Analysis of variance of deposition uniformity between leaves (in a 12-leaf batch) indicated a significant interaction for treatment × volume (\(P = 0.0359\)) and no significant interaction for treatment × horizontal canopy position (\(P = 0.217\)).

At 8 l tree\(^{-1}\), Break-Thru Union realised significantly better deposition uniformity (61.31%) than the control treatment (72.80 CV%), but similar to S240 (65.18 CV%). At 14 l tree\(^{-1}\), Break-Thru Union realised statistically better deposition uniformity than the water only treatment and S240, but not significantly better than Break-Thru Union (71.73 CV%) (Fig. 1).

![Fig. 1. Mean deposition quantity realised by the water only control treatment (Water), Break-Thru S240 (S240) and Break-Thru Union (Union) on leaves following sprays at 8, 14 and 20 l tree\(^{-1}\) on the inside and outside of dense tree canopies in a ‘Bahianina Araras’ navel orange orchard when compared to FPC\(_{50}\) and FPC\(_{75}\) benchmarks at 2.07% and 4.14%, respectively (Trial one).](image-url)
S240 (54.22 CV%) realised the best deposition uniformity, significantly better than that of the control treatment (71.42 CV%) and Break-Thru Union (64.13 CV%). Deposition uniformity realised by adjuvant treatments did not differ significantly from that of the control treatment at 20 l tree\(^{-1}\) (54.91–64.13 CV%; Table 3).

For the treatment \(\times\) horizontal canopy position interaction, Break-Thru S240 and Union improved deposition uniformity on outer canopy leaves (61.66 and 55.85 CV\%), respectively in relation to the water only treatment (66.07 CV\%), with Union improving uniformity significantly. On inner canopy leaves, both adjuvants (60.69 and 64.38 CV\%, respectively) improved deposition uniformity over that of the control treatment (70.35 CV\%), with Break-Thru S240 doing so significantly (Table 4).

### 3.2.3. Deposition efficiency

Analysis of variance of deposition efficiency indicated significant interactions for treatment \(\times\) horizontal canopy position \(\times\) vertical canopy position \((P = 0.0281)\) and for treatment \(\times\) volume \((P = 0.0147)\), but not for treatment \(\times\) horizontal canopy position \((P = 0.240)\).

For the treatment \(\times\) volume interaction, Break-Thru Union at 8 l tree\(^{-1}\) (0.58 FPC\% per l tree\(^{-1}\)) improved deposition efficiency significantly in relation to the deposition efficiency achieved by the control treatment (0.47 FPC\% per l tree\(^{-1}\)) and Break-Thru S240 (0.45 FPC\% per l tree\(^{-1}\)). At 14 l tree\(^{-1}\), adjuvant treatments did not differ from each other (0.42 FPC\% per l tree\(^{-1}\)) and significantly improved deposition efficiency compared to the control treatment (0.24 FPC\% per l tree\(^{-1}\)). At 20 l tree\(^{-1}\), Break-Thru Union again realised the best deposition efficiency; significantly better than the control treatment (0.27 FPC\% per l tree\(^{-1}\)) and S240 (0.22 FPC\% per l tree\(^{-1}\)) (Table 3).

Break-Thru Union realised significantly better deposition efficiency on outer canopy leaves (0.49 FPC\% per l tree\(^{-1}\)) than the control treatment (0.36 FPC\% per l tree\(^{-1}\)) and Break-Thru S240 (0.38 FPC\% per l tree\(^{-1}\)). On inner canopy leaves, both Break-Thru Union (0.41 FPC\% per l tree\(^{-1}\)) and S240 (0.35 FPC\% per l tree\(^{-1}\)) improved deposition efficiency significantly compared to the control treatment water only (0.29 FPC\% per l tree\(^{-1}\)) (Table 3).

For the interaction treatment \(\times\) horizontal canopy position \(\times\) vertical canopy position, best deposition efficiency was realised by Break-Thru Union (0.54 FPC\% per l tree\(^{-1}\)) on outer canopy leaves in the top of trees; significantly better than what was realised by the control treatment (0.35 FPC\% per l tree\(^{-1}\)) and Break-Thru S240 (0.40 FPC\% per l tree\(^{-1}\)) at this position. On outer canopy leaves in the middle position on trees, Break-Thru Union and the water only control treatment realised similar deposition efficiency (0.44 FPC\% per l tree\(^{-1}\)), significantly better than Break-Thru S240 (0.40 FPC\% per l tree\(^{-1}\)). On outer canopy leaves in the bottom of trees, Break-Thru Union and S240 realised the best deposition efficiency (0.39–0.50 FPC\% per l tree\(^{-1}\)), significantly better than that of the control treatment (0.30 FPC\% per l tree\(^{-1}\)).

On inner canopy leaves in tops of trees, Break-Thru Union (0.38 FPC\% per l tree\(^{-1}\)) realised the best deposition efficiency, significantly better than the control treatment (0.23 FPC\% per l tree\(^{-1}\)), whilst Break-Thru S240 realised an intermediate efficiency level (0.30 FPC\% per l tree\(^{-1}\)) that did not differ significantly from the control treatment and Union. Similar trends were observed in the middle and bottom of trees on inner canopy leaves, where Break-Thru Union realised the best deposition efficiency, significantly better than the control treatment, and with Break-Thru S240 being intermediate between the control treatment and Union (results not shown).

### 3.2.4. Deposition quality

Analysis of variance of deposition quality (ICD\%) indicated a significant interaction for treatment \(\times\) horizontal canopy position

### Table 3

Mean deposition quantity, uniformity, efficiency and quality realised by the control treatment (Water) and adjuvant treatments Break-Thru S240 (S240) and Break-Thru Union (Union) on leaves at different spray volumes 8-, 14- and 20 l tree\(^{-1}\) in less dense canopies in a ‘Palmer’ navel orchard (trial 2).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Deposition quantity (FPC%)</th>
<th>Deposition efficiency (FPC% normalised l tree(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 l tree(^{-1})</td>
<td>14 l tree(^{-1})</td>
</tr>
<tr>
<td>Water</td>
<td>3.73 de</td>
<td>3.42 e</td>
</tr>
<tr>
<td>S240</td>
<td>3.59 de</td>
<td>5.84 b</td>
</tr>
<tr>
<td>Union</td>
<td>4.66 cd</td>
<td>5.85 b</td>
</tr>
<tr>
<td>Water</td>
<td>72.80 a</td>
<td>71.42 a</td>
</tr>
<tr>
<td>S240</td>
<td>65.18 ab</td>
<td>54.22 d</td>
</tr>
<tr>
<td>Union</td>
<td>61.31 bcd</td>
<td>64.13 abc</td>
</tr>
</tbody>
</table>

### Table 4

Mean deposition quantity, uniformity, efficiency and quality realised by the control treatment (water) and adjuvant treatments Break-Thru S240 (S240) and Break-Thru Union (Union) on leaves on the inside and outside of less dense canopies in a ‘Palmer’ navel orchard (trial 2).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Deposition quantity (FPC%)</th>
<th>Deposition efficiency (FPC% normalised l tree(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outer canopy</td>
<td>Inner canopy</td>
</tr>
<tr>
<td>Water</td>
<td>4.63 c</td>
<td>3.77 d</td>
</tr>
<tr>
<td>S240</td>
<td>4.78 bc</td>
<td>4.54 c</td>
</tr>
<tr>
<td>Union</td>
<td>6.39 a</td>
<td>5.40 b</td>
</tr>
<tr>
<td>Water</td>
<td>66.07 ab</td>
<td>70.35 a</td>
</tr>
<tr>
<td>S240</td>
<td>61.66 bc</td>
<td>60.69 bc</td>
</tr>
<tr>
<td>Union</td>
<td>55.85 c</td>
<td>64.38 ab</td>
</tr>
</tbody>
</table>

\n\* For each parameter separately, values in each pair of columns for one variable followed by the same letter do not differ significantly \((P > 0.05)\) according to Fisher’s least significant difference test.
(P = 0.0435), but not for treatment x volume (P = 0.4434), no significant differences were observed between treatments (55.41 – 59.12 ICD %), except between the best and worst treatments, water only at 8 l tree⁻¹ and Union at 14 l tree⁻¹, respectively (Table 3).

Deposition quality levels on inner canopy leaves was lower (better) than on outer canopy leaves, with deposition on inner canopy leaves being similar for adjuvants and the water only treatment (53.33 – 54.80 ICD %). On outer canopy leaves, Break-Thru Union realised the lowest deposition quality (61.77 ICD %) significantly lower than that realised by Break-Thru S240 (58.79 ICD %). The water only treatment on outer canopy leaves was intermediate (60.98 ICD %) (Table 4).

3.2.5. Benchmarking

Deposition quantity results for the treatment x volume x horizontal canopy position interaction were compared to the FPC benchmarks (Van Zyl et al., 2013). On outer canopy leaves, all treatments realised deposition quantities above the FPC75 benchmark, except for Break-Thru S240 at 8 l tree⁻¹ and the control treatment at 14 l tree⁻¹, only realising deposition quantities above the FPC50 benchmark. On inner canopy leaves, Break-Thru Union realised deposition quantities above the FPC75 benchmark at all spray volumes. At 8 l tree⁻¹, the control treatment and Break-Thru S240 only realised deposition quantities above the FPC50 benchmark. At 14 l tree⁻¹, the control treatment deposited deposition quantities above the FPC50 benchmark, but below the FPC75 benchmark. At 20 l tree⁻¹, all treatments realised deposition quantities better than the FPC75 benchmark (Fig. 2).

4. Discussion

This study evaluated the influence of organosilicone adjuvants Break-Thru S240 and Break-Thru Union on deposition parameters at high and reduced spray volumes throughout citrus tree canopies. As in previous studies, the use of fluorometry, photomacrography, digital image analysis (Schutte et al., 2012; Van Zyl et al., 2013) and implementation of deposition benchmarks (for biological interpretation of deposition results) (Van Zyl et al., 2013) was highly effective in determining, evaluating and visualising deposition parameters of treatments. The fluorescent pigment used was proven by Van Zyl et al. (2013) to be an accurate tracer for contact copper fungicide deposition and was therefore used in this study.

Markedly different results were obtained between the two trials. Differences were largely ascribed to the variation in canopy density between the two trials. Unfortunately canopy density was not quantified. The crude 5-point scale used was effective in discerning between different canopy densities but should be improved in future studies. Differences between treatments were ascribed to the effects of adjuvant formulation on droplet formation (Spanoghe et al., 2007) and subsequently, canopy penetration (Gent et al., 2003) and deposition (De Ruiter et al., 1990; Holloway et al., 2000) of the fluorescent pigment on leaf surfaces. Droplet size was not determined in our study. The same spray machines were used in both trials and they were similarly calibrated whilst tractor speed and spray pressure used was to our knowledge, the most ideal for these spraying conditions. Tractor speed, PTO speed and spray pressure (2.4 km h⁻¹, 540 rpm and 1500 kPa, respectively) were kept constant throughout treatments and both trials to limit the variable effect on deposition parameters (Whitney et al., 1989; Salyani and Whitney, 1990). These factors are very important, since improper calibration, speed and pressure selection along with wrong spraying techniques, are usually the reason for poor deposition and therefore most treatment failures (Grout, 1997, 2003; Stover et al., 2002).

In both trials, deposition quantity generally increased with increase in spray volume for all treatments. Similar deposition was achieved throughout the top, middle and bottom of the canopy, except for better deposition achieved in the top of the canopy in trial one. This is testament to the efficacy of tower sprayers, as opposed to low-profile sprayers that generally deposited lower deposition quantities in tops of trees (P.H. Fourie, unpublished results). Deposition quantity was also found to be higher on outer canopy leaves than on inner canopy leaves with deposition at these positions increasing with spray volume. Our findings on spray deposition in citrus orchards support those of Farooq and Salyani (2002) previous studies. However, we found an increase in deposition on inner canopy leaves with an increase in spray

Fig. 2. Mean deposition quantity realised by the water only control treatment (Water), Break-Thru S240 (S240) and Break-Thru Union (Union) on leaves following sprays at 8,14 and 20 l tree⁻¹ on the inside and outside of pruned, less dense canopies in a 'Palmer' navel orange orchard when compared to FPC50 and FPC 75 benchmarks at 2.07% and 4.14%, respectively (Trial two).
volume, contradictory to that found by Salyani and Whitney (1988).

Canopy density had a direct effect on deposition quantity on outer and inner canopy leaves, with deposition quantity realised on outer and inner canopy leaves being higher and more consistent per treatment than that realised on dense canopies. This concurs with Salyani and Whitney (1990) and Farooq and Salyani (2002) who found higher variation in deposition at different positions in dense canopies. It has to be stated that different deposition measurement protocols were used in the studies mentioned but still similar outcomes were found.

The addition of Break-Thru S240 and Union to sprays at 8–14 and 20 l tree\(^{-1}\), did not improve deposition quantity or uniformity throughout the canopy (inner and outer canopy leaves) in dense canopies (trial one). In fact, a detrimental effect in terms of deposition quantity and uniformity was observed, especially with Break-Thru Union at 20 l tree\(^{-1}\) and on inner canopy leaves. However in less dense, pruned canopies, the addition of adjuvants to sprays had a beneficial effect with deposition quantity and uniformity realised being higher than that realised by the water only sprays. Improved deposition quantity on inner canopy leaves was especially evident with Break-S240 and Break-Thru Union at 14 l tree\(^{-1}\). A possible explanation for this phenomenon could be that droplets from sprays with Break-Thru S240 and Union impacting the dense canopy wall formed a film due to reduced surface tension and better adhesion of the spray mixture, which possibly led to increased run-off and reduced canopy penetration at the higher spray volumes. With the water only spray at these spray volumes, impacting water droplets on the canopy wall might have physically shattered on the hydrophobic leaf surfaces, since little to no film forming took place. Smaller shattered droplets could possibly drift more easily through the canopy wall onto inner canopy leaves. In less dense, pruned canopies, more uniform adjuvant droplets could be carried through the outer canopy since it was not captured by the dense outer canopy.

Deposition quantity following sprays at 20 l tree\(^{-1}\) was judged as sufficient in both trials as levels were above the FPC\(_{75}\) benchmark in all cases (Van Zyl et al., 2013; Figs. 1 and 2). However, when considering spray efficiency as well as benchmarks, spray deposition following sprays with S240 and Union at 14 l tree\(^{-1}\) in less dense, pruned canopies (trial 2) was most effective. The improvement of deposition uniformity in less dense compared with dense canopies was also evident. Deposition uniformity was improved with the addition of the two adjuvants at different spray volumes on the outside of the canopy, and most importantly on the inner canopy leaves in pruned canopies. In less dense canopies, this was the only case for Break-Thru Union, which improved deposition uniformity at all spray volumes and also on the inner and outer canopy leaves.

This study highlights the importance of canopy management. Canopy density was an important factor. More aerated, pruned canopies were essential for improved deposition, since spray mixture could readily deposit and penetrate the canopy due to improved air-movement. In more dense canopies, penetration of the “leaf wall” at all volumes was more difficult, causing excessive run-off on the outer canopy before spray mixture could readily deposit and penetrate the canopy. Run-off from outer canopy leaves could have been exacerbated by the addition of an adjuvant in these dense canopies, due to the reduction in surface tension, causing a run-off “flushing” effect as droplets impacted on leaf surfaces, not deflecting or fracturing off the leaf surface. Creating smaller fractured droplets that could more readily have been carried to the inside of the canopy. This phenomenon could theoretically be the reason for relatively poor deposition on the inner canopy leaves following adjuvant sprays in dense canopies (trial 1).

In terms of deposition efficiency, Break-Thru Union proved to be superior at all spray volumes in less dense canopies, especially at lower volume applications (8 l tree\(^{-1}\)), as also observed with deposition quantity. In dense canopies, the addition of the adjuvants did not improve deposition efficiency.

From the results obtained it is clear that canopy management is of cardinal importance for improving spray deposition, especially for reduced volume applications. If a canopy is not well managed and pruned (i.e. “spray friendly”), for example, does not have pruned windows to the inside of the canopy and is too dense, spray deposition will be negatively affected and will result in loss of effectiveness of spray application and through it, reduced disease control. Furthermore, the benefits of an adjuvant were especially evident in less dense “spray-friendly” canopies. A definitive beneficial was observed with the adjuvants, especially at lower spray volume applications (8 and 14 l tree\(^{-1}\)), indicating the potential to improve deposition quantity, efficiency and uniformity on the inner and outer canopy leaves, provided that the canopy is less dense, pruned.

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**References**


