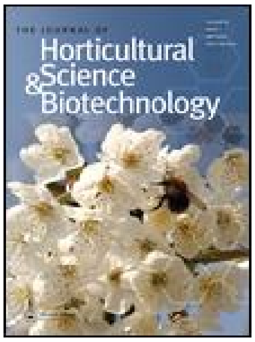

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Optimal timing of application of 2,4-D on ‘Navel’ sweet orange [*Citrus sinensis* (Osbeck)] reduces the size of the navel-end

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SUMMARY
‘Navel’ sweet orange [*Citrus sinensis* (Osbeck)] fruit with large, open, or protruding navel-ends are predisposed to splitting and navel-end rot, and provide an entry point that hampers the control of insect pests. A reliable method to reduce the size of navel-ends, without compromising tree health or fruit quality, would provide multiple benefits. The objective of this study, was to determine the optimal timing and concentration of foliar spray treatments with the synthetic auxin, 2,4-dichlorophenoxyacetic acid (2,4-D), to reduce the size of the navel-end on ‘Newhall Navel’ and ‘Washington Navel’ sweet orange fruit. The effects of 2,4-D treatment on fruit yield, tree health, and fruit quality, were also assessed. Treatments were applied to ‘Newhall Navel’ trees at a rate of 25 mg l^{-1} 2,4-D at 2-weekly intervals, starting at full bloom (FB), and continuing until 4 weeks after 100% petal drop (PD). On ‘Washington Navel’ trees, 2,4-D was applied at 15 mg l^{-1}, 25 mg l^{-1}, or 35 mg l^{-1} at FB, or at 100% PD. The timing of the application of 2,4-D to increase the percentage of closed navel-ends, and to reduce their size, was more important than the concentration. Application of 2,4-D at FB significantly increased the percentage of fruit with closed navel-ends, and reduced their size in both ‘Newhall Navel’ and ‘Washington Navel’ fruit. Later treatments were ineffective. Application of 2,4-D at FB had no effect on fruit diameter, fruit yield, fruit number, or fruit quality parameters, except for a decrease in the fruit diameter:length ratio. In addition, successful 2,4-D spray treatment led to a slight decrease in fruit juice content. The application of a foliar spray of 2,4-D at FB, and at concentrations as low as 15 mg l^{-1}, can be used to increase the percentage of closed navel-ends, reduce the number of culled fruit, and thereby improve the pack-out percentage for export quality ‘Navel’ sweet oranges.

The size of the navel-end is an important criterion for grading external fruit quality in ‘Navel’ sweet orange [*Citrus sinensis* (Osbeck)]. In addition, the presence of a large and/or open navel-end can lead to increased susceptibility to stylar-end decay (Lima and Davies, 1984; Lima *et al*., 1980; Wager, 1939) and fruit splitting (Cronje *et al*., 2013), and provides an entry point and refuge for insect pests (Soule and Grierson, 1986). Factors that influence the size of the navel-end include prevailing weather conditions in the orchard after fruit set (Wager, 1939), abnormal water relations (Wager, 1939), the bearing position of fruit on the tree (Lima and Davies, 1984; Wager, 1939), and insect damage (Wager, 1939).

The synthetic auxin, 2,4-dichlorophenoxyacetic acid (2,4-D) is used as a plant growth regulator (PGR) to influence plant growth and development during citrus fruit production by manipulating key physiological processes (El-Otmani *et al*., 2000). The main commercial uses for 2,4-D sprays during citrus production include increasing fruit size (Guardiola and García-Luis, 2000), prolonging the fruit harvest by reducing pre-harvest fruit drop (Anthony and Coggins, 1999; Coggins, 1981; Sarooshi, 1982), or as a post-harvest drench to retain the fruit calyx (Cronjé *et al*., 2005; Singh *et al*., 1977). 2,4-D is used at low concentrations that leave no hazardous residues, and pose a low risk to the environment (El-Otmani *et al*., 2000; Monselise, 1979).

A reduction in the size of the navel-end by 2,4-D was first reported by Krezdorn (1969), who showed that dipping ‘Dream Navel’ sweet orange flowers in a combination of 20 mg l^{-1} 2,4-D and 250 mg l^{-1} gibberellic acid (GA_3) reduced the size of the navel-end. To determine the efficacy of 2,4-D on the size of navel-ends in South Africa, a preliminary study showed that application of 25 mg l^{-1} 2,4-D at 100% petal drop (PD), increased the percentage of fruit with closed navel-ends, and reduced the average size of the navel-end in ‘Palmer Navel’, ‘Robyn Navel’, and ‘Lane Late Navel’ sweet oranges (Verreynne, 2008). A reduction in the size of the navel-end provides several advantages to growers such as higher yields, more effective insect control, and reductions in the incidence of fruit splitting (Cronjé *et al*., 2013) and stylar-end decay (Lima and Davies, 1984). However, results on the optimal timing and concentration of foliar sprays of 2,4-D to reduce navel-end size have been inconclusive.

The main objectives of the current study were to determine the optimal timing [early (FB) *vs.* late (during

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and after PD)] and concentration [low (15 mg l^{-1}), *vs.* high (35 mg l^{-1})] of a foliar spray of 2,4-D to reduce the size of the navel-end in two 'Navel' sweet orange cultivars over two seasons in a major production area. Additional objectives were to determine the effect of a foliar application of 2,4-D on fruit yield, tree health, and fruit quality.

MATERIALS AND METHODS

Plant material, experimental site and treatments

The experiments were conducted on 'Newhall Navel' and 'Washington Navel' sweet orange [*Citrus sinensis* (Osbeck)] trees, budded onto 'Rough Lemon' [*Citrus jambhiri* (Lush.)] rootstock at Citrusdal (32º30'S, 19º14'E), a citrus-producing region in the Western Cape Province of South Africa that experiences a typical Mediterranean-type climate.

Treatments applied to 'Newhall Navel' trees included an untreated control, 2,4-D at 25 mg l^{-1} at full bloom (FB), at 100% petal drop (PD), at 2 weeks after PD (2 WAPD), or at 4 weeks after PD (4 WAPD). Treatments applied to 'Washington Navel' trees were an untreated control, 2,4-D applied at 15 mg l^{-1}, 25 mg l^{-1}, or 35 mg l^{-1} at FB, or at 100% PD. Both experiments were carried out in commercial orchards under standard production practices over two growing seasons (2010 and 2011).

Spray material and method of application

An iso-octyl ester formulation of 2,4-D (Dow AgroSciences, Pretoria, South Africa) containing 480 g l^{-1} of active ingredient, and a non-ionic wetting agent (Break-Thru®; Villa Crop Protection, Kempton Park, South Africa) containing 1.0 g l^{-1} of polyether-polymethysiloxane copolymer as active ingredient, were applied at a rate of 0.05 ml l^{-1}. Foliar applications were applied using a hand-gun spray applicator until run-off (approx. 10 l per tree, or 5,000 l ha^{-1}). One or two buffer trees were left untreated between each treated tree. Eight trees per treatment were chosen as replicates for their uniformity in size, health, and flowering intensity, and the treatments were applied to the same trees in the following season.

Data collection

At commercial maturity, approx. 80 fruit were collected from all sectors of the tree canopy, on each replicate 'Newhall Navel' tree. The total weight of all 80 fruit was determined using an electronic balance (W22 Series; UWE Co., Hsin Tien, Taiwan), and the diameter of each sampled fruit was measured using electronic calipers (CD-6" C; Mitutoyo Corp., Tokyo, Japan). The percentage of fruit with closed navel-ends was calculated by dividing the number of fruit with closed navel-ends by the total number of fruit (80) evaluated per replicate tree. Thereafter, the total yield of fruit (kg $tree^{-1}$) was determined for each replicate tree of 'Newhall Navel' using an electronic balance. To estimate the total number of fruit on each replicat tree the total yield was divided by the average weight of the 80 fruit sampled. Yields were not determined for 'Washington Navel' sweet orange, as this was not practical due to the large size of the trees and high numbers of fruit, as well as the high number of replicates and treatments.

A representative sample of 12 randomly distributed fruit was collected from each replicate tree, at commercial maturity, in order to determine the effects of 2,4-D treatment on fruit quality. Pedicel diameters, fruit diameters and fruit lengths were measured using electronic calipers. The latter values were used to calculate fruit shape [i.e., the diameter:length (d:l) ratio]. Fruit were rated for any symptoms of granulation, a pre-harvest physiological disorder of citrus fruit that results in a decrease in extractable juice due to gel formation in the juice vesicles (Ritenour *et al.*, 2004). No granulation was observed in any of the cultivars in either season (data not shown).

Each fruit was cut in half along its equatorial plane, and the peel thickness (flavedo plus albedo) was measured at the equatorial region of each fruit using electronic calipers. Each fruit was juiced using a citrus juicer (Sunkist®, Chicago, IL, USA). The juice was strained through one layer of muslin cloth and the juice content [as a (w/w) percentage] was determined by dividing the weight of juice by the total weight of each fruit sample. Total soluble solids contents (TSSC; in ºBrix) were measured using a PR-32 Palette electronic refractometer (Atago Co., Tokyo, Japan). Titratable

TABLE I

*Effects of the timing of a single foliar spray of the synthetic auxin, 2,4-dichlorophenoxyacetic acid (2,4-D) on the percentage of fruit with closed navel-ends, the size of the navel-end, fruit diameter, fruit yield, and the total number of fruit in 'Newhall Navel' sweet orange [*Citrus sinensis *(Osbeck)] at Citrusdal, South Africa in 2010 and 2011*

Year/Treatment	Percentage of fruit with closed navel-ends (%)	Navel-end size (mm)	Fruit diameter (mm)	Yield (kg $tree^{-1}$)	Total fruit number per tree
2010					
Control (no 2,4-D)	12.9 c[†]	7.3 a	74.9 ns	135.9 ns	595 ns
25 mg l^{-1} 2,4-D at FB[‡]	36.2 a	4.7 d	75.6 ns	124.1 ns	561 ns
25 mg l^{-1} 2,4-D at PD	20.0 b	5.4 cd	75.7 ns	124.2 ns	555 ns
25 mg l^{-1} 2,4-D at 2 WAPD	17.6 bc	5.8 bc	74.1 ns	119.8 ns	533 ns
25 mg l^{-1} 2,4-D at 4 WAPD	14.4 bc	6.8 ab	74.2 ns	127.9 ns	575 ns
Significance (*P* value)	0.0001	0.0002	0.7334	0.5451	0.8659
2012					
Control (no 2,4-D)	10.9 b	8.5 a	81.9 ns	105.9 ns	376 ns
25 mg l^{-1} 2,4-D at FB	41.1 a	3.9 c	81.4 ns	119.0 ns	417 ns
25 mg l^{-1} 2,4-D at PD	18.7 b	6.0 b	82.6 ns	96.8 ns	345 ns
25 mg l^{-1} 2,4-D at 2 WAPD	10.0 b	7.2 ab	83.4 ns	94.0 ns	330 ns
25 mg l^{-1} 2,4-D at 4 WAPD	12.3 b	8.3 a	79.8 ns	124.1 ns	473 ns
Significance (*P* value)	0.0001	0.0005	0.5799	0.3396	0.4448

[†]Mean values (n = 8 trees per treaatment) followed by different lower-case letters in each column are significantly different at $P \leq 0.05$ by the LSD test.
[‡]FB (full bloom); PD, 100% petal drop; 2 WAPD, 2 weeks after 100% petal drop; 4 WAPD, 4 weeks after 100% petal drop.
ns, no significant difference.

TABLE II
*Effect of the timing of a single foliar spray of the synthetic auxin, 2,4-dichlorophenoxyacetic acid (2,4-D) on fruit quality in 'Newhall Navel' sweet orange [*Citrus sinensis *(Osbeck)] at Citrusdal, South Africa in 2010 and 2011*

Year/Treatment	Fruit diameter:length ratio	Pedicel diameter (mm)	Peel thickness (mm)	Fruit juice content [% (w/w)]	TSSC‡	Titratable acidity [TA (%)]	TSSC:TA ratio
2010							
Control (no 2,4-D)	0.91 ab†	3.4 a	7.3 a	45.1 a	9.9 ns	0.8 ns	12.2 ns
25 mg l^{-1} 2,4-D at FB‡	0.88 c	3.2 ab	7.2 a	42.6 b	9.9 ns	0.8 ns	12.0 ns
25 mg l^{-1} 2,4-D at PD	0.89 bc	2.9 c	6.8 a	42.3 b	10.0 ns	0.8 ns	12.0 ns
25 mg l^{-1} 2,4-D at 2 WAPD	0.92 a	2.7 d	7.1 a	45.3 a	9.8 ns	0.8 ns	11.9 ns
25 mg l^{-1} 2,4-D at 4 WAPD	0.91 ab	3.0 bc	6.0 b	42.9 b	9.8 ns	0.8 ns	11.5 ns
Significance (*P*-value)	0.0074	0.0001	0.0001	0.0076	0.9250	0.7872	0.5817
2011							
Control (no 2,4-D)	0.94 a	3.3 a	6.5	43.0 a	9.5 ns	0.7 ns	13.3 ns
25 mg l^{-1} 2,4-D at FB	0.91 b	3.2 a	6.9	39.0 b	9.4 ns	0.8 ns	11.8 ns
25 mg l^{-1} 2,4-D at PD	0.92 ab	3.4 a	6.7	35.0 c	9.7 ns	0.9 ns	11.2 ns
25 mg l^{-1} 2,4-D at 2 WAPD	0.93 a	2.9 ab	7.2	39.2 b	9.3 ns	0.8 ns	11.8 ns
25 mg l^{-1} 2,4-D at 4 WAPD	0.95 a	2.7 b	7.1	41.9 a	9.7 ns	0.7 ns	12.6 ns
Significance (*P*-value)	0.0191	0.0402	0.1785	0.0001	0.4736	0.0744	0.1262

†Mean values (n = 8 trees per treatment) followed by different lower-case letters in each column are significantly different at $P \leq 0.05$ by the LSD test.
‡FB, full bloom; PD, 100% petal drop; 2 WAPD, 2 weeks after 100% petal drop; 4 WAPD, 4 weeks after 100% petal drop; TSSC, total soluble solids content (in ºBrix).
ns, no significant difference.

The Journal of Horticultural Science and Biotechnology 2015.90:619-625.

acidity (TA) was determined by titrating 20 ml of the extracted juice with 0.1 M sodium hydroxide using phenolphthalein as an indicator. The TSSC:TA ratio was then calculated.

Experimental design and analysis

Each treatment was applied to eight single replicate trees of each cultivar arranged in a randomised complete block design, with one-or-two buffer trees between each treated tree, and one buffer row of trees between each treatment row. Analysis of variance (ANOVA) was performed using the PROC GLM procedure in SAS software (Version 9.1; SAS Institute, Cary, NC, USA). Mean separations were carried out using the least significant difference (LSD) test, where applicable, at $P \leq 0.05$.

RESULTS

'Newhall Navel'

In 2010, all 2,4-D treatments, except that at 4 WAPD, reduced the size of the navel-end, compared to the controls (Table I). In 2011, only the 25 mg l^{-1} 2,4-D at FB or at PD caused a significant reduction in the size of the navel-end (Table I). Application of 25 mg l^{-1} 2,4-D, irrespective of the time of treatment, had no effect on fruit yield, or on fruit diameter (Table I).

Fruit shape was significantly altered by 2,4-D at FB (i.e., with a reduced d:l ratio), whereas later treatments had no effect on fruit shape (Table II). In 2010, all treatments, except 2,4-D at FB, significantly reduced the diameter of the fruit pedicel. Peel thickness was significantly reduced by 2,4-D at 4 WAPD in 2010, with no effect of any treatment in 2011 (Table II). All 2,4-D treatments, except application after PD, significantly reduced the juice percentage (w/w) in 2010 and 2011. No 2,4-D treatment had any effect on TSSC, TA, or on the TSSC:TA ratio (Table II).

'Washington Navel'

In 2010, all 2,4-D treatments at FB significantly increased the percentage of fruit with closed navel-ends compared to the untreated controls or to application at PD (Table III). In 2011, all 2,4-D treatments, except 15 mg l^{-1} at PD, significantly reduced the size of the navel-end. None of the treatments affected fruit diameter in either season (Figure 1; Table III).

Treatments with 2,4-D did not affect fruit shape (the d:l ratio) or fruit pedicel diameter, except for a significant increase with 35 mg l^{-1} 2,4-D at PD in 2011 (Table IV). Spraying with 25 mg l^{-1} 2,4-D at FB significantly increased peel thickness in 2010 and in 2011, while application at PD reduced peel thickness in 2011 (Table IV). In 2010, no 2,4-D treatment significantly affected the fruit juice (w/w) percentage; however, in 2011, 15 mg l^{-1} 2,4-D at FB or PD significantly increased, and 35 mg l^{-1} 2,4-D at PD reduced the fruit juice (w/w) percentage. Fruit juice percentage was also reduced by increasing the concentration of 2,4-D. No 2,4-D treatment had any effect on TSSC, TA, or the TSSC:TA ratio (Table IV).

TABLE III
*Effects of the concentration and the timing of a single foliar spray of the synthetic auxin, 2,4-dichlorophenoxyacetic acid (2,4-D) on the percentage of closed navel-ends, the size of the navel-ends, and fruit diameters in 'Washington Navel' sweet orange [*Citrus sinensis *(Osbeck)] at Citrusdal, South Africa in 2010 and 2011*

Year/Treatment	Percentage of fruit with closed navel-ends	Navel-end size (mm)	Fruit diameter (mm)
2010			
Control (no 2,4-D)	28.4 bc†	3.7 a	71.3 ns
15 mg l^{-1} 2,4-D at FB‡	53.3 a	2.1 bc	70.7 ns
25 mg l^{-1} 2,4-D at FB	49.9 a	2.1 bc	73.3 ns
35 mg l^{-1} 2,4-D at FB	54.2 a	1.8 c	72.2 ns
15 mg l^{-1} 2,4-D at PD	26.7 bc	3.2 ab	70.4 ns
25 mg l^{-1} 2,4-D at PD	39.7 ab	3.1 ab	70.9 ns
35 mg l^{-1} 2,4-D at PD	19.8 c	3.7 a	71.4 ns
Significance (*P* value)	0.0005	0.0071	0.3799
2011			
Control (no 2,4-D)	8.7 b	8.9 a	77.2 ns
15 mg l^{-1} 2,4-D at FB	36.0 a	4.9 cd	78.9 ns
25 mg l^{-1} 2,4-D at FB	33.8 a	4.1 d	79.8 ns
35 mg l^{-1} 2,4-D at FB	46.2 a	3.8 d	78.9 ns
15 mg l^{-1} 2,4-D at PD	8.7 b	7.9 ab	82.2 ns
25 mg l^{-1} 2,4-D at PD	15.9 b	6.9 b	79.3 ns
35 mg l^{-1} 2,4-D at PD	15.9 b	6.4 bc	76.1 ns
Significance (*P* value)	0.0013	0.0001	0.3876

†Mean values (n = 8 trees per treatment) followed by different lower-case letters in each column are significantly different at $P \leq 0.05$ by the LSD test.
‡FB, full bloom; PD, 100% petal drop.
ns, no significant difference.

TABLE IV
*Effects of the concentration and timing of a single foliar spray of the synthetic auxin, 2,4-dichlorophenoxyacetic acid (2,4-D,) on fruit quality in 'Washington Navel' sweet orange [*Citrus sinensis *(Osbeck)] at Citrusdal, South Africa in 2010 and 2011*

Year/Treatment	Fruit diameter:length ratio	Pedicel diameter (mm)	Peel thickness (mm)	Fruit juice content [% (w/w)]	TSSC‡	Titratable acidity [TA (%)]	TSSC:TA ratio
2010							
Control	1.0	2.9	5.6 b†	42.6	12.0	0.9	13.9
15 mg l^{-1} 2,4-D at FB‡	1.0	2.8	5.6 b	41.9	11.4	0.8	13.9
25 mg l^{-1} 2,4-D at FB	1.0	3.1	6.7 a	42.2	11.4	0.9	12.5
35 mg l^{-1} 2,4-D at FB	1.0	2.7	5.3 b	41.5	12.1	0.8	14.4
15 mg l^{-1} 2,4-D at PD	1.0	2.7	5.0 b	42.2	11.9	0.8	14.1
25 mg l^{-1} 2,4-D at PD	1.0	3.2	5.2 b	39.0	12.3	0.8	14.7
35 mg l^{-1} 2,4-D at PD	1.0	2.9	5.6 b	42.1	11.8	0.8	14.4
Significance (*P* value)	0.5753	0.1899	0.0319	0.3908	0.1214	0.5763	0.1886
2011							
Control	1.0	2.8 b	6.0 b	41.4 c	11.7	1.0	11.7
15 mg l^{-1} 2,4-D at FB	1.0	2.5 b	4.9 d	44.8 ab	11.4	1.0	11.6
25 mg l^{-1} 2,4-D at FB	1.0	2.5 b	6.2 a	42.4 bc	10.8	1.0	11.3
35 mg l^{-1} 2,4-D at FB	1.0	2.7 b	5.6 bc	42.0 bc	11.6	1.0	12.1
15 mg l^{-1} 2,4-D at PD	1.0	2.6 b	5.0 d	45.5 a	11.3	1.0	11.3
25 mg l^{-1} 2,4-D at PD	1.0	2.7 b	4.9 d	39.4 cd	11.1	1.0	11.0
35 mg l^{-1} 2,4-D at PD	1.0	3.5 a	5.3 cd	36.5 d	11.9	1.1	11.3
Significance (*P* value)	0.0682	0.0001	0.0001	0.0001	0.0819	0.5680	0.6259

†Mean values (n = 8 trees per treatment) followed by different lower-case letters in some columns are significantly different at $P \leq 0.05$ by the LSD test.
‡FB, full bloom; PD, 100% petal drop; TSSC, total soluble solids content (ºBrix).

The Journal of Horticultural Science and Biotechnology 2015.90:619-625.

Effects on tree health and stylar abscission

A foliar spray of 2,4-D resulted in leaf curling on current season Spring growth (Figure 2A), but with no effect on mature leaves (Figure 2B). The response was more pronounced on 'Washington Navel' orange fruit in treatments with higher 2,4-D concentrations. Flower PD and fruit style abscission were delayed when 2,4-D was applied before the start of fruit style abscission, and, in some cases, the styles persisted on fruit up to, or close to fruit maturity.

DISCUSSION

Treatment effects on navel-ends

Foliar sprays of 2,4-D significantly increased the percentage of fruit with closed navel-ends in 'Newhall Navel' and 'Washington Navel' sweet orange, as well as reducing the average size of the navel-end when applied at FB. Although 2,4-D at PD consistently reduced the size of the navel-end, 2,4-D at 2 WAPD or 4 WAPD did not have a consistent or significant effect. These results agreed with a preliminary study on 'Palmer Navel', 'Robyn Navel', and 'Lane Late Navel' sweet orange (Verreynne, 2008). The mode of action of 2,4-D in preventing navel-ends from developing as open, appeared to be related to delayed abscission of the fruit style, as achieved by applying 2,4-D at FB, or shortly thereafter, at PD. If the fruit style abscised early during fruit development (Figure 1A), a more open navel-end developed (Figure 1B) than when the style remained attached for longer. At 2 WAPD and at 4 WAPD, most of the fruit styles had already abscised, and 2,4-D treatment was ineffective at reducing navel-end size (Figure 1C).

Endogenous auxins, such as indole-acetic acid (IAA), regulate the abscission of plant organs by blocking the capacity of ethylene to induce abscission events that lead to premature fruit drop, or fruit style abscission (Borroto *et al*., 1981; Goren, 1993). Application of 2,4-D, as in this study, is thought to mimick the role of IAA, and retard natural abscission of the fruit style (Figure 1D).

A similar delay in fruit style abscission was observed in mandarin [*Citrus reticulata* (Blanco)] in response to foliar application of 2,4-D (Stander *et al*., 2014). In mandarin, the delay in fruit style abscission increased the integrity of the fruit peel at the stylar-end, and hence, reduced the incidence of fruit splitting (Stander *et al*., 2014), a physiological disorder that involves cracking of the peel at the stylar-end and splitting-open of the fruit (Cronjé *et al*., 2013).

In addition to the delay in fruit style abscission, a change in fruit shape (i.e., a reduced d:l ratio) resulted from spraying 2,4-D at FB. A similar change in 'Navel' orange fruit shape by 2,4-D was reported by Verreynne (2008), whereas 2,4-D caused 'Washington Navel' (Stewart *et al*., 1951) and 'Marisol Clementine' mandarin (Stander *et al*., 2014) fruit to become more cylindrical compared to untreated fruit. Considine and Brown (1981), showed that the tension exerted by the increase in fruit volume during fruit development was highest at the polar regions (i.e., the stylar- and stem-end) of the fruit, and that the fruit peel was therefore more likely to initiate rupturing at these points. Concomitantly, the alteration in fruit morphology resulting from 2,4-D was shown to be a possible mode of action for the reduction in fruit splitting in mandarin (Stander *et al*., 2014). In addition to more closed navel-ends, as reported in this study, 2,4-D treatment could also contribute to reducing the incidence of navel-end fruit splitting in 'Navel' sweet orange, as reported by Cronjé *et al*. (2013).

Effects of 2,4-D on fruit size, fruit yield and fruit quality

Foliar application of 2,4-D has been reported to increase fruit size in citrus (Guardiola and García-Luis, 2000; Stewart and Klotz, 1947). However, Guardiola and García-Luis (2000) reported that not all cultivars exhibited similar responses, and the effect of 2,4-D on fruit size was, to a large extent, dependent on the time of application. This was also evident in the current study, with the application of 2,4-D having no significant effect on fruit diameter in either cultivar at fruit maturity. Furthermore, no 2,4-D treatment affected fruit yields or total fruit numbers. The application of 2,4-D after the natural physiological fruit drop period has been shown to result in fruit thinning in 'Washington Navel' orange

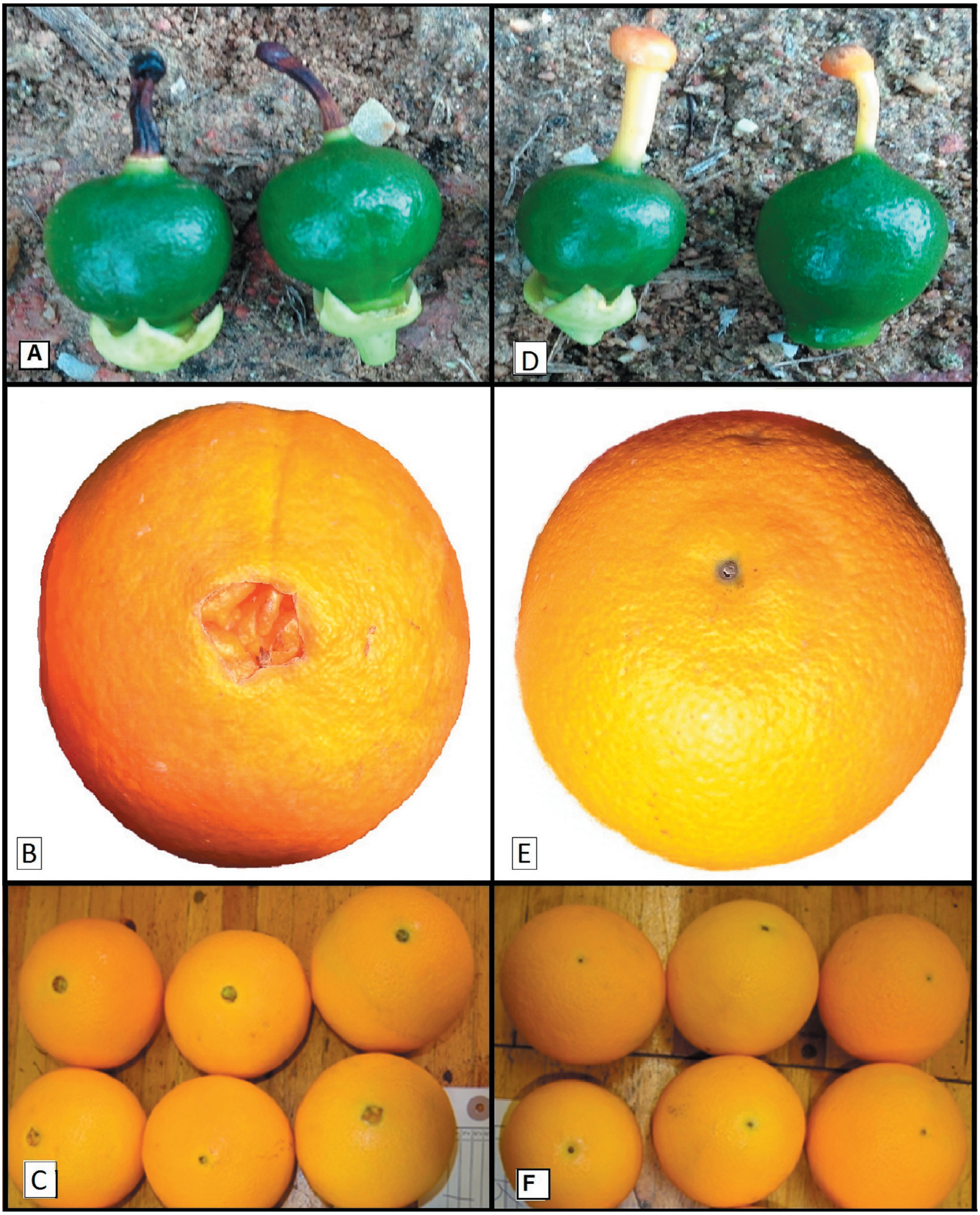

FIG. 1
Effect of a single foliar spray application of 15 mg l^{-1} 2,4-dichlorophenoxyacetic acid (2,4-D) on the percentage and size of open navel-ends on 'Washington Navel' sweet orange [*Citrus sinensis* (Osbeck)] fruit at Citrusdal, South Africa in 2011. Application of 2,4-D after the start of fruit stylar abscission (Panel A) was ineffective at reducing the percentage of fruit with open navel-ends (Panel B), as well as average size of the navel-ends (Panel C). Applying 2,4-D at full bloom, prior to the abscission of fruit styles delayed fruit style abscission (Panel D), increased the percentage of fruit with closed navel-ends (Panel E), as well as the size of the navel-ends (Panel F).

(Stewart *et al.*, 1951). No thinning effect of 2,4-D was observed in the present study, probably due to the earlier timing of application, prior to the natural physiological fruit drop period.

Previous studies on 'Washington Navel' sweet orange reported an increase in rind thickness by 2,4-D (Stewart *et al.*, 1951), although at a much higher concentration (> 75 mg l^{-1}). In this study, peel thickness was not

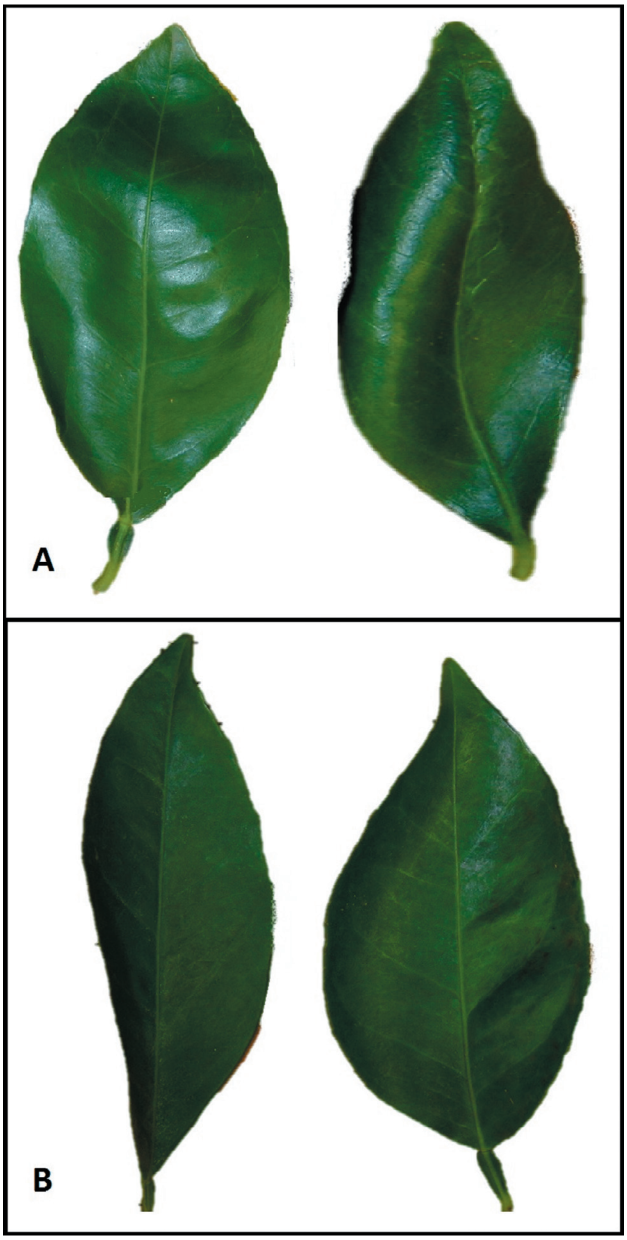

FIG. 2
Effect of a single foliar application of 2,4-dichlorophenoxyacetic acid (2,4-D) on leaf curling in 'Washington Navel' sweet orange [*Citrus sinensis* (Osbeck)] at Citrusdal, South Africa in 2011. Leaf curling developed on new vegetative growth after a single foliar application of 2,4-D at 35 mg l^{-1} (Panel A). At the time of harvest, no curled leaves were present (Panel B), suggesting that the response was temporary.

consistently affected by 2,4-D and, in some cases, 2,4-D reduced rind thickness. Reductions in the juice content of 'Navel' sweet orange due to 2,4-D treatment have been reported (Stewart and Klotz, 1947; Stewart *et al.*, 1951; Verreynne 2008). However, only 2,4-D at FB reduced the juice content in 'Newhall Navel', with no such effect in 'Washington Navel'. No 2,4-D treatment had any effect on TSSC, TA, or the TSSC:TA ratio, in either cultivar.

Effects of 2,4-D on tree health

Stewart and Klotz (1947) reported the curling of young, expanding 'Valencia' sweet orange leaves after treatment with 2,4-D. The curling of leaves is caused by an epinastic response to 2,4-D that results in the downward and inward rolling of young leaves at the margins. In this study, 2,4-D caused a similar curling of leaves, but only on new vegetative growth (Figure 2A). However, at the time of harvest, no curled leaves were present (Figure 2B), suggesting that the response was only temporary. Leaf curling was more pronounced at higher concentrations of 2,4-D (e.g., 35 mg l^{-1}) in 'Washington Navel' orange trees, and was barely visible at lower concentrations (15 mg l^{-1}).

CONCLUSION

Foliar applications of 2,4-D at FB, irrespective of the concentration applied, consistently increased the percentage of fruit with closed navel-ends, and reduced their size in 'Newhall Navel' and in 'Washington Navel' sweet orange. After the start of fruit style abscission, 2,4-D treatment at 100% PD, 2 WAPD, or 4 WAPD was ineffective. The timing of 2,4-D spray to increase the percentage of closed navel-ends and reduce their size was therefore more important than the concentration. Spraying 2,4-D at FB had no adverse effects on internal or external fruit quality, except for a reduction in juice content in 'Newhall Navel' by ≤ 4%.

Future research should focus on evaluating lower concentrations of 2,4-D to obtain a similar efficacy without reducing the juice content. Foliar application of 2,4-D at FB, at concentrations as low as 15 mg l^{-1}, at a rate of 10 l per tree, can be used to increase the percentage of fruit with closed navel-ends in 'Navel' sweet orange, to reduce the number of culled fruit, and to improve the pack-out percentage for export. Future research should also determine and quantify any benefits relating to the prevalance of closed navel-ends such as better insect pest control.

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