Efficacy of ACC (1-aminocyclopropane-1-carboxylic acid) as a Chemical Thinner Alone or Combined with Mechanical Thinning for Japanese Plums (*Prunus salicina*)

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Abstract. Thinning is a labor-intensive and expensive, but important practice in Japanese plum production requiring new thinning strategies. The purpose of this study was to evaluate a new chemical thinner 1-aminocyclopropane-1-carboxylic acid (ACC) on ‘Laetitia’, ‘Fortune’, and ‘African RoseTM’. ACC was also combined with 6-benzyl adenine (6-BA) and in one season on ‘African RoseTM’ with mechanical thinning using the Darwin 300TM or hand thinning during bloom. All the foliar applications were made when the average fruitlet diameter was 7–10 mm using a spray volume of 1000 L·ha⁻¹ under slow drying conditions. Significant thinning effects were found in all the trials conducted over the two seasons. ACC consistently reduced the hand-thinning requirement at commercial hand thinning in both seasons in ‘African RoseTM’. In the second season there was a linear decrease in yield and an increase in fruit size as the ACC rate increased from the low to medium rate before flattening off. The combination treatment of ACC and the Darwin 300TM used in the ‘African RoseTM’ trial thinned more aggressively, improved fruit size and shifted harvest earlier. The yield however was not lower than that of the control treatment. 6-BA was included in all trials to prevent ACC-induced leaf drop, and generally did not thin fruitlets, except in the case of ‘Laetitia’ where the combination with ACC resulted in stronger thinning. Cultivars differed in their sensitivity to ACC and the rate for each cultivar should be determined separately. The recommended ACC rate for ‘African RoseTM’ would be 600 µL·L⁻¹ and for ‘Laetitia’ 400 µL·L⁻¹. For ‘Fortune’ a rate recommendation is not possible at this stage, thus further trials should be conducted. No broken stones were observed in fruit in any trial. Also, no leaf drop/phytotoxicity was recorded in any trial when ACC was applied during cool, slow-drying conditions.

Annual cropping of fruit trees is very important and to achieve this, flower or fruit thinning is practiced. By reducing the number of fruit on the tree, the remaining fruit will develop to the optimal size of higher quality and return bloom the next season will be adequate for a good crop load (Njoroge and Reighard, 2008). Thinning can be done at various times, i.e., prebloom, full bloom, and postbloom, and the cheapest and earliest method of thinning is pruning (Njoroge and Reighard, 2008). However, even when stone fruit trees are properly

pruned, they still often set too many fruit (DeJong and Grossman, 1994). The severity of thinning as well as the timing is closely linked to the reproductive and vegetative performance of the tree (Costa and Vizzotto, 2000). Appropriate thinning must therefore be done annually, to achieve the advantages it has on flower number, fruit size, fruit quality, fruit-to-shoot ratio, and in preventing alternate bearing (Costa et al., 1983; Seehuber et al., 2011).

Chemical thinning plums would reduce hand thinning substantially, but currently, chemical thinners available for stone fruit thinning are limited (Seehuber et al., 2011). One chemical thinning approach for plums is to use gibberellins, e.g., gibberellic acid (GA₃), but results are often inconsistent.

GA₃ applied during flower induction will reduce flowering the next season and indirectly reduce the number of fruit, which will lead to a reduction in hand-thinning costs (González-Rossia et al., 2006). Therefore, to be effective, GA₃ must be applied when flower-bud differentiation can be affected (Costa and Vizzotto, 2000). The main reason why GA₃ sprays are not used as a chemical thinner is “thinning” is performed long before bloom and climatic conditions, i.e., frost during bloom, might still negatively influence fruit set of the fewer blossoms (Byers et al., 1990; Costa and Vizzotto, 2000).

A preferred alternative approach is using blossom thinners that burn flower parts and prevent fertilization and therefore fruit set (Southwick et al., 1996). The surfactant, Tergitol-TMN-6, significantly reduced fruit set and increased fruit size in ‘Empress’ plums at various rates (7.5 and 12.5 mL·L⁻¹) (Fallahi et al., 2006). Tergitol-TMN-6 is effective over a wide range of phenological stages from full bloom to petal fall, which allows for a longer window of application (Wilkins et al., 2004). The current recommendation for stone fruit is to apply Tergitol-TMN-6 at 75% to 80% full bloom at 7.5–12.5 mL·L⁻¹ (Fallahi et al., 2006), but in South Africa, blossom thinners have not been very successful.

A number of chemical thinners are used commercially on pome fruit, e.g., ethephon, 6-benzyladenine (6-BA) and naphthalene acetic acid (NAA) (Byers and Carbaugh, 1991). Ethephon releases ethylene which stimulates fruit abscission (Wertheim, 2000). Ethephon at 250 µL·L⁻¹ applied to ‘Victoria’ plums at full bloom did not reduce fruit set, whereas 75 µL·L⁻¹ Ethephon combined with 10 µL·L⁻¹ NAA applied 27 d after full bloom did reduce fruit set significantly. Both treatments advanced fruit maturity (Meland, 2007). The return bloom the next season, however, was not improved by either treatment (Meland and Birken, 2010). A new chemical thinner currently being evaluated in pome fruit is ACC (Schupp et al., 2012), but its efficacy on Japanese plums is unknown. According to Adams and Yang (1979), ACC is effectively converted to ethylene in apple tissue. Further studies on mung beans confirmed that ACC, a precursor of ethylene, increased the corresponding rate of ethylene production (Yoshii and Imaseki, 1981).

Mechanical thinning is a relatively new development in the stone fruit industry and can be used to remove both flowers and fruitlets (Miller et al., 2011; Theron et al., 2015). Hand thinning could be reduced by mechanical thinning by 28%. In addition, the effect of mechanical thinning is immediate and not influenced by climatic conditions (Martin et al., 2010). Inconsistent results, however, have hampered the successful implementation of mechanical thinning in stone fruit (Reighard and Byers, 2009). Miller et al. (2011), Baugher et al. (2009, 2010) and Schupp et al. (2008) found added

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economic benefits in producing larger peach fruit while reducing follow-up hand thinning when they combined mechanical bloom thinning with green-fruit hand thinning (Miller et al., 2011; Baugher et al., 2009; Baugher et al., 2010; Schupp et al., 2008). The Darwin™ does not thin selectively enough and will therefore not replace hand thinning completely (Miller et al., 2011). More recently De Villiers (2014) evaluated the Darwin 300™ on Japanese plums and was able to significantly reduce the time it took to hand thin trees. In two of the three trials on the plums ‘African Rose™’ [cv. ARC PR-4 (PR00-01)] and ‘Laetitia’, it also resulted in an increase in fruit size (De Villiers, 2014), but the tree training system has to be adapted to the machine.

The purpose of this study was to evaluate the efficacy of chemical thinners, i.e., ACC and 6-BA applied at the fruitlet stage to various Japanese plum cultivars on fruit set, yield, and fruit quality. ACC is a precursor of ethylene and increases ethylene production (Adams and Yang, 1979), which can lead to leaf drop, therefore 6-BA was included in this study to try and prevent phytotoxicity/leaf drop possibly induced by the ACC (Zieslin and Gottesman, 1983). The chemical thinning treatments were also combined with mechanical thinning using the Darwin 300™ or hand thinning during bloom on ‘African Rose™’.

Materials and Methods

Plant material and site description for the 2013/2014 season. In the 2013/2014 season, a trial was conducted on the Japanese plum cultivar African Rose™ on the farm Sandrivier (33°35′58.0″ S, 18°55′40.1″ E) near Wellington in the Western Cape, South Africa. The mature, uniform flowering ‘African Rose™’ trees, on Mariana rootstock, were planted in 2009 at a spacing of 3.5 m × 1 m. The planting system used for this orchard is a V-system and trees are trained to a 9-wire hedge with 10% ‘Pioneer’ trees as the cross pollinator.

Experimental layout for the 2013/2014 season. Two products were evaluated, viz., ACC (Valent BioSciences Corporation, Libertyville, IL) and 6-BA (MaxCel®, Valent BioSciences Corporation). Seven treatments were used in a randomized complete block design with eight single tree replications. The treatments were as follows: 1) an untreated control, 2) 6-BA (100 µL·L⁻¹), 3) 6-BA (300 µL·L⁻¹), 4) ACC (150 µL·L⁻¹), 5) ACC (300 µL·L⁻¹), 6) ACC (500 µL·L⁻¹), and 7) 6-BA (100 µL·L⁻¹) plus ACC (500 µL·L⁻¹) as a tank mix. All applications were made on 11 Sept. 2013 at a fruitlet diameter of 7–10 mm. Hand thinning was done on 1 Oct. 2013 and trees were harvested on 18 Nov. 2013.

Plant and site description for the 2014/2015 season. Trials were conducted on the Japanese plum cultivars African Rose™, Fortune, and Laetitia. Mature, uniform-flowering ‘Fortune’ and ‘African Rose™’ trees on the farm Sandrivier (33°35′58.0″ S,

18°55′40.1″ E) near Wellington in the Western Cape, South Africa, were used. A uniform-flowering ‘Laetitia’ orchard on Fransmanskraal (33°35′34.7″ S, 18°49′06.4″ E), Devon Valley, near Stellenbosch was selected. The trial on ‘African Rose™’ was in the same orchard as in the previous season, but on different trees. The ‘Fortune’ on Mariana rootstocks were planted in 2005 at 4.5 m × 0.75 m and trained to a V-hedge system. The cross pollinator in this orchard was 10% ‘Angeleno’. The ‘Laetitia’ trees on Mariana rootstocks were relatively young, planted in 2011 at a spacing of 3.25 m × 1.5 m and trained to a palmette system. The cross pollinator was ‘Sunbreeze’ and planted every alternate row.

Experimental layout for the 2014/2015 season. The ‘African Rose™’ trial consisted of 10 treatments in a randomized complete block design with 10 replicates. The treatments were as follows: 1) an untreated control, 2) Darwin 300™ at full bloom (12 Aug. 2014), 3) hand flower thinning, where every second flower cluster was removed at full bloom, 4) 6-BA (100 µL·L⁻¹), 5) ACC (400 µL·L⁻¹), 6) ACC (600 µL·L⁻¹), 7) ACC (800 µL·L⁻¹), 8) 6-BA (100 µL·L⁻¹) plus ACC (800 µL·L⁻¹) as a tank-mix, 9) Darwin 300™ at full bloom plus ACC (600 µL·L⁻¹), and 10) Darwin 300™ at full bloom plus ACC (800 µL·L⁻¹). For the mechanical thinning treatments, each replicate consisted of five trees with the middle tree used to record data. The tractor speed was 4.8 km·h⁻¹ and rotor speed 160 rpm. All chemical applications were made on 3 Sept. 2014 at a fruitlet diameter of 8–10 mm. Hand thinning was done on 16 Sept. 2014 and trees were harvested on 10, 14, and 17 Nov. 2014. The ‘Fortune’ and ‘Laetitia’ trials each consisted of six treatments in a randomized complete block design with 10 replicates as follows: 1) an untreated control, 2) 6-BA (100 µL·L⁻¹), 3) ACC (200 µL·L⁻¹), 4) ACC (400 µL·L⁻¹), 5) ACC (600 µL·L⁻¹), and 6) 6-BA (100 µL·L⁻¹) plus ACC (600 µL·L⁻¹) as a tank mix. All chemical applications were made on 1 Oct. 2014 for ‘Fortune’ and on 3 Oct. 2014 for ‘Laetitia’ at a fruitlet diameter of 8–10 mm. Hand thinning was done on 15 and 17 Oct. 2014 and trees were harvested on 22 and 26 Dec. 2014 and 14 Jan. 2015 for ‘Fortune’ and ‘Laetitia’, respectively.

Treatment application. All the foliar applications were made using a motorized knapsack sprayer (STIHL, Pietermaritzburg, South Africa) when the average fruitlet size was 7–10 mm at a rate of 1000 L·ha⁻¹ under slow drying conditions when the temperature was between 10 and 15 °C. At least one tree was left between the treated trees and a buffer row, where more than one row was needed for the trial, to prevent drift effects. The conditions following the applications were favorable for at least 5 d with temperatures above 18 °C.

Data collection. In all trials, the same data were recorded. After the application of the treatments, a period of at least 2 weeks was allowed for fruitlets to drop. Hand thinning

was done according to standard commercial practices during which the largest fruitlets were retained, remaining fruitlets spaced and thinned to the required number per tree. All fruitlets thinned by hand were collected and brought back to the laboratory, weighed and counted. At each commercial harvest date, the yield per tree was recorded. A sample of 30 fruit per harvest was brought to the laboratory for further evaluation. The following was recorded on each fruit: fruit weight, diameter, length, firmness, and the incidence of broken stones. Fruit firmness was determined using the GÜSS texture analyzer with a 11-mm tip (Güss electronic model GS 20; Strand, South Africa), while broken stones were recorded as either present or not. Return bloom was not recorded as all trees flowered profusely the following spring and no visual differences were seen.

Statistical analysis. The data were analyzed using SAS Enterprise guide 5.1 (SAS Institute Inc., Cary, NC) using the linear model procedure and the pairwise *t* test to determine the least significant difference when the *F*-statistic indicated significance at *P* < 0.05. Single df, and orthogonal and polynomial contrasts were fitted where applicable.

Results

Results for the 2013/2014 season: ‘African Rose™’. The highest rate of ACC (500 µL·L⁻¹) significantly reduced the number of fruitlets that had to be thinned by hand during commercial hand thinning compared with the control (Table 1). The increase in ACC rate resulted in a linear decrease in the number of fruitlets that needed hand thinning. 6-BA did not thin significantly, not even at the high rate. The addition of 6-BA to the high rate of ACC did not affect the thinning efficacy (Table 1) and no leaf drop/phytotoxicity was observed in this trial. No significant differences were found in total yield per tree (Table 1) or yield at either of the two harvest dates or harvest distribution (data not shown). There was no significant difference in the average fruit weight from a combined fruit sample from the two harvest dates (Table 1).

Results from the 2014/2015 season: ‘African Rose™’. Both the Darwin 300™ and the hand flower thinning treatment at full bloom as well as all ACC applications significantly reduced the number of fruitlets that had to be thinned by hand during commercial hand thinning compared with the control (Table 2). With increasing ACC rate, a linear decrease in the number of fruitlets that needed hand thinning was found. The combination of the ACC and Darwin 300™ significantly reduced the number of fruitlets that had to be thinned compared with the ACC treatments on their own (*P* = 0.028) (Table 2). 6-BA did not result in significant thinning and the addition of 6-BA to the high rate of ACC did not affect the thinning efficacy (Table 2). No leaf drop/phytotoxicity was observed in this trial. All the treatments, except 6-BA, significantly increased the

Table 1. Effect of 6-benzyladenine (6-BA) and 1-aminocyclopropane carboxylic acid (ACC) on hand-thinning requirement, yield per tree, and average fruit weight at harvest in 'African Rose™' plum at Sandrivier, Wellington District, South Africa (2013/2014).

Treatment	Avg number of fruitlets thinned by hand	Total yield per tree (kg)	Avg fruit wt (g) over two harvests
Control	1,799 a	13.7 ^{ns}	54.1 ^{ns}
6-BA 100 µL·L ⁻¹	1,868 a	12.9	54.7
6-BA 300 µL·L ⁻¹	1,747 ab	13.3	52.8
ACC 150 µL·L ⁻¹	1,852 a	14.0	56.7
ACC 300 µL·L ⁻¹	1,572 abc	13.9	56.0
ACC 500 µL·L ⁻¹	1,424 c	13.1	55.8
6-BA + ACC ^z	1,490 bc	12.1	52.3
Significance level	0.0177	0.7402	0.1720
Least significant difference 5%	302	—	—
BA vs. ACC	0.0537	0.5059	0.0517
ACC linear	0.0075	0.4191	0.6463
ACC quadratic	0.4596	0.8092	0.8155
Control vs. rest	0.2281	0.6285	0.6347

^z6-BA (100 µL·L⁻¹) + ACC (500 µL·L⁻¹).

Table 2. Effect of 6-benzyladenine (6-BA), 1-aminocyclopropane carboxylic acid (ACC), and Darwin 300™ on hand-thinning requirement, fruitlet weight at hand thinning, and yield per tree in 'African Rose™' plum at Sandrivier, Wellington District, South Africa (2014/2015).

Treatment	Avg number of fruitlets thinned by hand	Avg wt of hand thinned fruitlets (g)	Total yield per tree (kg)
Control	2,597 a	1.4 e	9.9 abc
Darwin at full bloom	1,359 c	1.8 c	8.6 cd
Flower thinning	1,890 b	1.7 cd	11.1 a
6-BA 100 µL·L ⁻¹	2,844 a	1.5 de	11.4 a
ACC 400 µL·L ⁻¹	1,371 c	1.8 c	10.6 ab
ACC 600 µL·L ⁻¹	1,088 cd	1.9 c	11.2 a
ACC 800 µL·L ⁻¹	802 de	1.8 c	8.0 d
6-BA + ACC ^z	835 de	2.0 bc	10.0 abc
Darwin + ACC 600 µL·L ⁻¹	650 e	2.3 a	8.9 bcd
Darwin + ACC 800 µL·L ⁻¹	527 e	2.1 ab	7.9 d
Significance level	<0.0001	<0.0001	0.0002
Least significant difference 5%	325.88	0.29	1.85
ACC vs. ACC + Darwin	0.0028	0.0002	0.0691
ACC linear	0.0008	0.7373	0.0070
ACC quadratic	0.9896	0.7770	0.0178
Control vs. rest	<0.0001	<0.0001	0.8664

^z6-BA (100 µL·L⁻¹) + ACC (800 µL·L⁻¹).

average weight of the thinned fruitlets significantly compared with the control (Table 2). The average weight of the thinned fruitlets for the ACC and Darwin 300™ combination treatments was significantly higher than that of the same ACC rates on their own.

Only the highest rate of ACC (800 µL·L⁻¹) on its own and in combination with the Darwin 300™ reduced the total yield per tree compared with the control (Table 2). There was a quadratic trend in total yield per tree with increasing ACC rate with only the highest rate reducing yield significantly. On average, all treatments altered the harvest distribution compared with the control (Table 3). The percentage of fruit that was harvested during the first harvest for the ACC and the Darwin 300™ combination treatments was significantly higher than that of the control. Almost the opposite could be observed during the third harvest, where the percentage fruit harvested for the untreated control was the highest, but not significantly higher than 6-BA treatment, ACC 400 µL·L⁻¹, and ACC 600 µL·L⁻¹ (Table 3). All the treatments increased the average fruit weight

except for 6-BA and again the average fruit weight increased quadratically with the ACC rate until 600 µL·L⁻¹, and ACC 600 µL·L⁻¹ being the highest fruit weight of the ACC treatments (Table 3). Also, the average weight of the two higher ACC rates (600 and 800 µL·L⁻¹) and two ACC and Darwin 300™ combination treatments had significantly larger fruit compared with the rest of the treatments. The average fruit weight at the first harvest increased from the lower to the two higher rates of ACC and the average fruit weight of the ACC treatments at the first harvest was significantly higher than that of the control (data not shown). Broken stone levels were very low, ranging from 0% to 0.12% (data not shown).

'Fortune'. The two higher rates of ACC significantly reduced the number of fruitlets that had to be thinned by hand during commercial hand thinning compared with the control (Table 4). The increase in ACC rate resulted in a linear decrease in the number of fruitlets that required hand thinning. 6-BA did not result in significant thinning, but increased the hand-thinning requirement, thus increased fruit set. The

addition of 6-BA to the high rate of ACC did not have an additional thinning effect. No leaf drop/phytotoxicity was observed in this trial. These treatments had no significant effect on the average weight of the hand-thinned fruitlets (Table 4).

The two higher ACC rates and the combination treatment with 6-BA reduced the total yield per tree significantly when compared with the control, thus resulting in a quadratic response to ACC (Table 4). The harvest distribution was not altered by any treatment, but there was a trend for advancement of harvest with increasing ACC rate ($P = 0.051$) (Table 5). The ACC 600 µL·L⁻¹ and ACC and 6-BA combination treatment increased the average overall fruit weight when compared with the control, whereas the 6-BA and two lower ACC rates did not have any significant effect on the average fruit weight (Table 5). No differences were found in average fruit weight at the first harvest date, whereas the two higher ACC rates and the combination treatment with 6-BA increased the average fruit weight significantly during the second harvest, and there was a linear increase in fruit weight as the ACC rates increased (data not shown). These treatments had no effect on the incidence of broken stones (data not shown).

'Laetitia'. The two higher ACC rates significantly reduced the number of fruitlets that had to be thinned by hand during commercial hand thinning compared with the control (Table 6). The increase in ACC rate resulted in a linear decrease in the hand-thinning requirement. 6-BA application did not result in significant thinning. The ACC and 6-BA combination treatment thinned significantly more aggressively than the ACC alone. All treatments reduced the average weight of the thinned fruitlets significantly when compared with the control (Table 6). No leaf drop/phytotoxicity was observed in this trial. The highest ACC rate and the combination treatment reduced the total yield significantly (Table 6). The two higher ACC rates and the combination treatment increased average fruit weight significantly compared with the control with a linear increase in fruit weight as the ACC application rate increased (Table 6). No broken stones were observed in any fruit.

Discussion

'African Rose™'. 'African Rose™' is a self-fertile, early Japanese plum (Culdevco, 2009), and therefore sets excessive fruit. In addition, the short fruit development phase tends to result in small fruit size. The highest ACC rate of 500 µL·L⁻¹, both alone or in combination with 6-BA, were the only two treatments that had a significant thinning effect in the first season. This was clear from the number of fruitlets that needed to be hand thinned. Exogenously applied Ethephon increases ethylene levels in plants (Wertheim, 1997), thereby stimulating fruit abscission (Wertheim, 2000). A similar response to ACC, a precursor of ethylene, is expected.

Table 3. Effect of 6-benzyladenine (6-BA), 1-aminocyclopropane carboxylic acid (ACC), and Darwin 300™ on yield distribution and average fruit weight of 'African Rose™' plum at Sandrivier, Wellington District, South Africa (2014/2015).

Treatment	Percentage of fruit picked at first harvest	Percentage of fruit picked at second harvest	Percentage of fruit picked at third harvest	Avg fruit wt (g) over three harvests
Control	13.5 c	26.4 ^{ns}	60.1 a	52.5 c
Darwin at full bloom	24.8 bc	32.7	42.6 bc	59.8 b
Flower thinning	25.2 bc	30.7	44.1 bc	57.2 b
6-BA 100 µL·L ⁻¹	19.1 bc	29.1	51.8 ab	52.5 c
ACC 400 µL·L ⁻¹	18.3 bc	34.8	46.9 abc	59.5 b
ACC 600 µL·L ⁻¹	15.3 c	33.7	51.0 ab	66.1 a
ACC 800 µL·L ⁻¹	19.8 bc	42.3	37.9 bcd	64.9 a
6-BA + ACC ^z	27.6 abc	37.2	35.2 cd	59.5 b
Darwin + ACC 600 µL·L ⁻¹	32.4 ab	34.8	32.8 cd	66.2 a
Darwin + ACC 800 µL·L ⁻¹	40.1 a	33.4	26.5 d	64.3 a
Significance level	0.0161	0.2523	0.0017	<0.0001
Least significant difference 5%	14.73	—	15.57	4.26
ACC vs. ACC + Darwin	0.0006	0.3147	0.0090	0.8858
ACC linear	0.8399	0.1704	0.2524	0.0134
ACC quadratic	0.5568	0.3089	0.2078	0.0391
Control vs. rest	0.0455	0.0556	0.0016	<0.0001

^z6-BA (100 µL·L⁻¹) + ACC (800 µL·L⁻¹).

Table 4. Effect of 6-benzyladenine (6-BA) and 1-aminocyclopropane carboxylic acid (ACC) on hand-thinning requirement, fruitlet weight at hand thinning, and average yield per tree of 'Fortune' plum at Sandrivier, Wellington District, South Africa (2014/2015).

Treatment	Avg number of fruitlets thinned by hand	Avg wt of hand thinned fruitlets (g)	Total yield per tree (kg)
Control	427 b	7.8 ^{ns}	12.3 a
6-BA 500 µL·L ⁻¹	606 a	6.8	10.9 a
ACC 200 µL·L ⁻¹	451 b	7.2	12.3 a
ACC 400 µL·L ⁻¹	239 c	7.8	8.7 b
ACC 600 µL·L ⁻¹	188 c	7.4	8.1 b
6-BA + ACC ^z	149 c	7.9	7.8 b
Significance level	<0.0001	0.1404	<0.0001
Least significant difference 5%	123.64	—	1.60
Control vs. ACC	0.0011	0.5100	<0.0001
ACC linear	<0.0001	0.7600	<0.0001
ACC quadratic	0.1362	0.2597	0.0345

^z6-BA (100 µL·L⁻¹) + ACC (600 µL·L⁻¹).

Meland and Birken (2010) found effective thinning of 'Victoria' plums after application of Ethephon at 250, 375, and 500 µL·L⁻¹ at full bloom and 125, 250, and 375 µL·L⁻¹ at 10–12 mm fruitlet diameter. Schupp et al. (2012) found promising results when ACC was used to thin 'Golden Delicious' apple trees where the thinning effect increased linearly with increasing rate of ACC. In the subsequent season (2014–15), we applied higher rates of ACC (600 and 800 µL·L⁻¹), but still a large number of fruit had to be thinned by hand. During both seasons, the most effective ACC treatments showed the benefit of early thinning in that the hand-thinned fruitlets were already larger at the time of hand thinning. We included the mechanical and hand flower thinning to reduce fruit number earlier and with the settings chosen for the Darwin 300™ it was expected that using the machine at full bloom would have a similar thinning effect as the 50% hand flower thinning treatment, and both these treatments resulted in larger fruitlets at commercial hand thinning when compared with the control. De Villiers (2014) also evaluated the Darwin 300™ on 'African Rose™' plums with various rotor speeds, viz. 220, 250, and 280 rpm and all treatments

significantly reduced the required hand-thinning time compared with the control. Seehuber et al. (2011) also successfully mechanically thinned European plum 'Ortenauer'. The benefit of early flower thinning on fruit growth was demonstrated by Grossman and DeJong (1995) on peach trees, therefore, the combination treatments of the Darwin 300™ at full bloom followed by a later ACC application were included in this trial and this enhanced the thinning efficacy and resulted in significantly larger fruitlets at commercial hand thinning compared with the ACC and Darwin 300™ treatments on their own. In both seasons, the 6-BA treatment did not have any thinning effect, which was expected (S. Reynolds, personal communication). Also no leaf drop was observed, therefore, the addition of 6-BA to the ACC did not have any beneficial or negative effects.

During the first season, no significant effects on total yield, harvest distribution, fruit weight were found with any ACC treatments. Therefore, the thinning obtained with the 500 µL·L⁻¹ did not over thin, thus justifying the decision to increase the ACC rates in the second season. However, with the increase in ACC rates in the following

season, there was a quadratic effect on the yield with the highest ACC rate of 800 µL·L⁻¹ over thinning and resulting in a significantly lower yield than the control. The yield of the 600 µL·L⁻¹ ACC-treated trees did not differ significantly from the control, thus indicating this as the recommended ACC rate for 'African Rose™'. The yield of the combination treatment of the Darwin 300™ and ACC 600 µL·L⁻¹ did not differ from the control even though the thinning effect of the combination treatment was significantly higher than the treatments on their own. The Darwin 300™ on its own and 50% hand flower thinning during bloom did not significantly reduce yield compared with the control. De Villiers (2014) found similar results for total yield when using the Darwin 300™. With the increase in ACC rates in the 2014/2015 season, a linear decrease in yield was observed as the rate of ACC increased, which should make it possible to find the correct rate of ACC depending on the yield required.

The combination treatments between the Darwin 300™ and ACC did advance harvest and almost 30% more fruit was picked at the first harvest date. Fruit firmness was not significantly affected (data not shown), indicating that fruit maturity was advanced by the heavy thinning treatments resulting in advanced harvesting, which is a known response to thinning (Costa and Vizzotto, 2000; Wünsche et al., 2000).

In the 2014/2015 season, all the treatments had a significant and positive effect on fruit size except for the 6-BA treatment. Pavel and DeJong (1993) found that individual fruit size increased in trees with lower crop loads compared with the fruit of unthinned trees and this is a well-known response to fruit thinning (Costa et al., 1983; Costa and Vizzotto, 2000). The Darwin 300™ treatment increased the average fruit weight significantly compared with the control, thus corresponding with what De Villiers (2014) found. The two combination treatments of the Darwin 300™ with ACC 600 and 800 µL·L⁻¹, and these two ACC rates alone significantly increase fruit size compared with the untreated control, but also more so than the flower thinning treatments alone and the lowest ACC (400 µL·L⁻¹) rate. The quadratic effect on fruit size that was observed for the ACC-treated trees indicated that the 600 µL·L⁻¹ application had the best effect on fruit size of all the ACC treatments with no further gain above this concentration and again confirming that this should be the recommended rate for 'African Rose™'.

'Fortune'. The two higher ACC rates successfully reduced hand fruit thinning as did the combination of ACC and 6-BA. However, in this trial, there was no effect on the average weight of the individual fruitlets thinned by hand. It appears though that these treatments over thinned as the total yield of these treatments was significantly lower compared with the control. It would appear that 'Fortune' is more sensitive to ACC than 'African Rose™'. These treatments did not alter the harvest distribution

Table 5. Effect of 6-benzyladenine (6-BA) and 1-aminocyclopropane carboxylic acid (ACC) on yield distribution and average fruit weight at harvest of 'Fortune' plum at Sandrivier, Wellington District, South Africa (2014/2015).

Treatment	Percentage of fruit picked at first harvest	Percentage of fruit picked at second harvest	Avg fruit wt (g)
Control	21.9 ^{ns}	78.1 ^{ns}	88.7 bc
6-BA 500 $\mu\text{L}\cdot\text{L}^{-1}$	18.4	81.6	85.4 c
ACC 200 $\mu\text{L}\cdot\text{L}^{-1}$	18.3	81.7	91.9 abc
ACC 400 $\mu\text{L}\cdot\text{L}^{-1}$	31.2	68.7	95.3 ab
ACC 600 $\mu\text{L}\cdot\text{L}^{-1}$	29.8	70.2	99.9 a
6-BA + ACC ^z	27.5	72.5	100.4 a
Significance level	0.0938	0.0938	0.0064
Least significant difference 5%	—	—	8.90
Control vs. ACC	0.2911	0.2911	0.0239
ACC linear	0.0510	0.0510	0.0780
ACC quadratic	0.1512	0.1512	0.8780

^z6-BA (100 $\mu\text{L}\cdot\text{L}^{-1}$) + ACC (600 $\mu\text{L}\cdot\text{L}^{-1}$).

Table 6. Effect of 6-benzyladenine (6-BA) and 1-aminocyclopropane carboxylic acid (ACC) on hand-thinning requirement, average weight of thinned fruitlets, yield per tree, and average fruit weight at harvest of 'Laetitia' plum at Fransmanskraal, Stellenbosch District, South Africa (2014/2015).

Treatment	Average number of fruitlets thinned by hand	Average weight of hand thinned fruitlets (g)	Total yield per tree (kg)	Average fruit weight (g)
Control	385 a	4.6 a	10.7 ab	73.0 c
6-BA 500 $\mu\text{L}\cdot\text{L}^{-1}$	412 a	3.9 b	11.7 a	73.2 c
ACC 200 $\mu\text{L}\cdot\text{L}^{-1}$	350 a	3.9 b	10.9 ab	74.5 c
ACC 400 $\mu\text{L}\cdot\text{L}^{-1}$	217 b	3.5 b	9.7 bc	87.4 b
ACC 600 $\mu\text{L}\cdot\text{L}^{-1}$	171 b	3.7 b	8.2 c	91.5 b
6-BA + ACC ^z	70 c	3.9 b	5.8 d	97.6 a
Significance level	<0.0001	0.0561	<0.0001	<0.0001
Least significant difference 5%	89.09	0.72	1.95	5.75
Control vs. ACC	<0.0001	0.0025	0.0099	<0.0001
ACC linear	0.0002	0.6548	0.0076	<0.0001
ACC quadratic	0.2661	0.3791	0.9020	0.0824

^z6-BA (100 $\mu\text{L}\cdot\text{L}^{-1}$) + ACC (600 $\mu\text{L}\cdot\text{L}^{-1}$).

in this trial, but did influence fruit size. The average fruit weight of the ACC treated trees was significantly larger than that of the control trees. This is not surprising as it is well known, as stated earlier, that to achieve fruit of adequate size, regulation of crop load is essential (Day and DeJong, 1998). Even though the lower rate of ACC (200 $\mu\text{L}\cdot\text{L}^{-1}$) did not adequately thin the trees, the 400 $\mu\text{L}\cdot\text{L}^{-1}$ ACC resulted in over thinning, but on average increased fruit size by regulating the crop load (Day and DeJong, 1998), indicating that somewhere in between 200 and 400 $\mu\text{L}\cdot\text{L}^{-1}$ ACC might be the recommended thinning rate for 'Fortune' plums. There was no need for the addition of 6-BA to prevent leaf drop. As a cautionary note, it should be mentioned that this particular orchard did not yield very well during the particular season.

Laetitia. This cultivar does not set as heavily as African RoseTM, therefore, slightly lower rates of ACC were used in a pilot trial in 2013/2014, some promising thinning responses, which led to the full statistical trial the following season. However, the severe leaf drop observed in the pilot trial was important and indicated that applying ACC midday at temperatures exceeding 30 °C could result in phytotoxicity and applications should be made early morning or during the evening at lower temperatures. During the second season, the two higher ACC rates (400 and 600 $\mu\text{L}\cdot\text{L}^{-1}$) significantly thinned

fruitlets. 6-BA treatment alone did not have any thinning effect when compared with the control, but had an additive thinning effect in combination with the high ACC rate. Because this 'Laetitia' orchard was relatively young and still growing vigorously, the 6-BA could have further stimulated shoot growth (Elfving and Cline, 1993; Green et al., 1992) when added to the ACC causing even more competition between the shoots and fruitlets resulting in more severe thinning. The IAA transport out of all the newly released lateral buds may have correlatively inhibited IAA transport from fruit, thus leading to the abscission of some of them (Bangerth, 2000). Unfortunately, we did not monitor shoot growth in our trials. Another reason for the additive effect could be the surfactants in the 6-BA formulation resulting in more uptake of the ACC, but this response was not observed in 'African RoseTM' or 'Fortune'.

The total yield of the trees receiving the 400 $\mu\text{L}\cdot\text{L}^{-1}$ ACC application did not differ significantly from the control and would be the recommended rate for 'Laetitia' plums as hand thinning was reduced by 44% without a negative effect on yield. Even though the highest ACC rate (600 $\mu\text{L}\cdot\text{L}^{-1}$) did reduce the number of fruitlets that still needed to be thinned by hand more than the 400 $\mu\text{L}\cdot\text{L}^{-1}$ ACC application, the total yield for the high rate was significantly lower compared with the control. The severe thinning effect achieved with the combination treatment

(ACC and 6-BA) did lead to over thinning as indicated by the significantly lower yield than that of the control and the highest ACC rate application. The two higher ACC concentrations (400 and 600 $\mu\text{L}\cdot\text{L}^{-1}$) had a positive effect on fruit weight. The largest fruit obtained with 600 $\mu\text{L}\cdot\text{L}^{-1}$ might not have compensated for the lower yield, and it is important to find the balance between yield and average fruit size (Njoroge and Reighard, 2008).

Conclusion

We obtained promising fruitlet thinning with ACC on Japanese plums. The data indicated that for a self-fertile cultivar like African RoseTM, a higher rate of 600 $\mu\text{L}\cdot\text{L}^{-1}$ should be used and possibly also combined with mechanical flower thinning. 'Laetitia' could be thinned effectively by using a lower rate of 400 $\mu\text{L}\cdot\text{L}^{-1}$, whereas in the case of 'Fortune', even a lower rate could be enough. Although positive results regarding yield and fruit size were obtained for both 'African RoseTM' and 'Laetitia', there is some concern regarding the yield in the 'Fortune' trial. Therefore, the recommended use of ACC might be cultivar specific and further trials are needed before final recommendations can be made. In addition, it could be interesting to evaluate earlier application, i.e., at fruitlet diameter of 4–6 mm, especially in 'African RoseTM' that has a very short fruit growth period. The Darwin 300TM shows promise. The hand thinning required following the Darwin 300TM was $\approx 50\%$ less than that of the untreated control, without negatively influencing yield and with a positive effect on fruit size. No leaf drop/phytotoxicity was observed when ACC was applied during cool conditions, but high temperatures should be avoided.

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