Modeling Loosening of Sweet Orange with CMNP: Variation in Fruit Detachment Force

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The abscission agent 5-chloro-3-methyl-4-nitro-1H-pyrazole (CMNP) was applied at 200 and 300 ppm to ‘Hamlin’ trees in three trials from December through the end of January and to ‘Valencia’ in three trials from March through April to determine the spatial and temporal variation in fruit detachment force (FDF) and fruit drop up to 5 d after application. Average FDF varied from 18 to 97 N for ‘Hamlin’ and 42 to 119 N for ‘Valencia’ before CMNP was applied. A univariate analysis was used to determine the upper and lower 99% confidence limits and means for every sampling date. Linear regressions fitted to the three regressions for each cultivar and CMNP concentration were statistically significant at the \( P < 0.05 \) or \( P < 0.01 \) level. The slopes and CMNP concentrations were subjected to ANOVA, and the lack of an interaction indicated that the rate of loosening was similar regardless of initial FDF. The slopes for the lower and upper confidence limits and mean for ‘Valencia’, but the slope of the lower confidence limit was lower than for the upper confidence limit and mean for ‘Hamlin’, indicating that ‘Hamlin’ fruit with low initial FDF loosen slower than fruit with higher initial FDF. An exponential function was found to fit well to fruit drop over time with regression coefficients ranging from 0.75 to 0.99. We propose that the relationships developed here would be useful in developing a predictive tool for mechanical harvesters with catch frames that minimizes the sum of fruit drop and fruit left in the tree after harvest.

Harvest costs and labor supply are major challenges confronting the Florida citrus industry with labor accounting for 40% of the total production cost (Muraro, 1997). Labor costs and availability concerns have stimulated interest in developing mechanical systems for harvesting citrus for the processing industry, especially sweet oranges [Citrus sinensis (L.) Osbeck]. Economic analysis indicates that harvest machines reduce harvesting costs by 15% to 20% (Brown, 2005). Of the 193,000 ha of sweet oranges grown commercially in Florida for the processing industry (Anonymous, 2008) about 7% are mechanically harvested (FDOC, 2008). Expansion of hectares mechanically harvested would be aided by improving removal rates, which studies have shown range between 50% and 98% of total yield (Whitney, 1975, 2000, 2003; Whitney et al., 2001; Wilson, 1978).

Research has been conducted for several decades to improve consistency and crop removal, mainly by altering the design of harvesters and through development of abscission agents that would promote loosening. No abscission agents are currently registered for use on citrus in Florida, but a label is being sought for 5-chloro-3-methyl-4-nitro-1H-pyrazole (CMNP), which has been shown in many studies to be an effective loosening agent in sweet orange (Burns et al., 2005; Holm and Wilson, 1977; Kender, 1996; Burns, 2005; Burns et al., 2006). In addition, among the many abscission agents tested, CMNP has been shown to selectively loosen mature fruit without causing injury to young tissues, foliage, or newly developing fruit in ‘Valencia’ (Holm and Wilson, 1977; Kender, 1996; Wilson, 1973). CMNP efficacy is a function of several factors including concentration, coverage, post spray precipitation and air temperature (Alferez et al., 2005; Fallahi et al., 1999; Sites and Reitz, 1949, 1950). It is not known whether CMNP applications loosen fruit uniformly throughout the canopy and how the initial variation in FDF changes over time. Knowing how CMNP affects fruit with high initial FDF will be important for understanding how to maximize crop removal by mechanical harvesters. For mechanical harvesters equipped with catch frames, determining the rate of loosening by CMNP for fruit with low initial FDF will be important for maximizing recovery, defined as the percentage of the total yield that is captured by the catch frames. The objectives of this study were to determine 1) the variability in FDF of fruit before spray; 2) how FDF changes after CMNP spray over time; and 3) the pattern of fruit drop. The results are discussed with respect to development of a model for scheduling CMNP applications as an aid for mechanical harvesting.
Materials and Methods

**Plant material and culture.** Seventeen-year-old ‘Hamlin’ and 21-year-old ‘Valencia’ trees grafted on Swingle rootstock (*Citrus paradisi × Poncirus trifoliata*) and Carrizo citrange (*Citrus sinensis* (L.) Osb. × *Poncirus trifoliata* (L.) Raf.) rootstock, respectively, were used. The ‘Hamlin’ trees were spaced 6.7 × 3.4 m in Ft. Drum sand (siliceous, hyperthermic Aeric Endoaquents) and Malabar fine sand (siliceous, hyperthermic Gossarenic En-doaquels) located at Silver Strand North grove, block B3 (lat. 26N 23’ 15’’, long. 81W 23’ 49’’), Immokalee, FL. The ‘Valencia’ trees were spaced 6.7 × 3.7 m and grown on a Wabasso fine sandy soil (siliceous, active, hyperthermic Alfic Aqualuods) located at Ranch One Cooperative Inc., block P26 (lat. 26N 19’ 39’’, long. 81W 22’ 10’’), Immokalee, FL.

**Treatments.** CMNP (ASI-100 17 EC, 17.2% w/w) was applied at 200 and 300 ppm with 0.1% (w/v) Activator-90 (alkyphenol ethoxylate, alcohol ethoxylate, and oil fatty acid; Loveland Products, Inc., Greeley, CO) as an adjuvant, sprayed to drip on ‘Hamlin’ and ‘Valencia’ trees. CMNP was applied using a skid sprayer (model no. 268173B, Northern Tool and Equipment Co., Faribault, MN). There was also an unsprayed control. There were a total of 36 ‘Hamlin’ and 36 ‘Valencia’ trees used in this experiment. CMNP was applied on six dates, once in December and twice in January for ‘Hamlin’, and once in March and twice in April for ‘Valencia’. On each date, each CMNP treatment was applied to four trees that were selected in a randomized complete-block design with a buffer tree between each spray tree.

**FDF and fruit drop.** Once or twice a day starting immediately before CMNP application to 5 d after CMNP application, 10 fruit were randomly clipped from each tree at the stem and FDF measured immediately using a force gauge (Force One digital force gauge; Wagner Instruments, Greenwich, CT) as described previously (Pozo et al., 2004). Fruit that dropped to the ground prior to harvesting were collected and weighed.

**Statistical analysis.** Variation in FDF among fruit was conducted by pooling fruit for each CMNP treatment and each sampling date. Although the RCBD was ignored for statistical purposes, the field design ensured that variation with tree location was minimized among CMNP treatments.

The mean and upper and lower 99% confidence limits for FDF of all fruit from each trial and CMNP treatment were determined using the univariate analysis procedure of the Statistical Analysis System (SAS Institute Inc., Cary, NC). To determine the change in the mean and upper and lower confidence limits over time after each CMNP application, the values from the univariate analysis were fitted with a linear regression using the regression procedure of SAS. To determine if the rate of loosening (slopes) of the mean and upper and lower confidence limits were parallel, the slopes of the regression for each cultivar were subjected to the GLM procedure of SAS with the interaction between CMNP and the slopes of the lines included in the model. In this analysis, application date served as the replication.

The change in fruit drop over time was determined using an exponential function and the NLIN procedure of SAS. The exponential function was of the form:

\[ \text{Fruit drop} (\%) = e^{(C \times \text{hat})} \]

where C is a constant determined by NLIN and “hat” is hours after treatment. The regression coefficient for each function was calculated using the formula:

\[ R^2 = 1 - \frac{\text{residual sums of squares}}{\text{total sums of squares}} \]

Results and Discussion

FDF varied considerably before CMNP was applied on each sampling date (Table 1). The ‘Hamlin’ fruit had lower average lower and upper 99% confidence limits than ‘Valencia’. The average lower and upper 99% confidence limits for ‘Hamlin’ were 18 N and 97 N, respectively, and the average lower and upper 99% confidence limits for ‘Valencia’ were 42 N and 119 N, respectively. In general, FDF declined with later CMNP application dates for both cultivars as the fruit matured.

All linear regressions fitted to the lower and upper 99% confidence limits and the mean FDF values were significant at the P < 0.05 or P < 0.10 level of significance (Fig. 1). The regression coefficients ranged from 0.16 to 0.78, which were reduced in part by factors that affected the goodness-of-fit, such as air temperature (Ebel and Burns, 2008; Yuan and Burns, 2004) and diurnal fluctuations in FDF that were shown to correlate with air temperature (Pozo et al., 2007), but that were not included in the analysis. The slopes of all regressions were negative, indicating that CMNP loosened the fruit and that the loosening continued for the entire sampling period.

To determine if all fruit loosened uniformly, we compared the rate of loosening of the upper and lower confidence limits and the mean for each cultivar. The interaction for the CMNP treatment and slopes were not significant for ‘Hamlin’ and ‘Valencia’ indicating that CMNP did not differentially affect the rate of loosening for fruit held tightly (high initial FDF) or loosely (low initial FDF) (Table 2). CMNP at 300 ppm loosened ‘Hamlin’ fruit more quickly as indicated by the steeper slope (–0.418 N/h) than 200 ppm (–0.265 N/h). There was no difference between 200 and 300 ppm for ‘Valencia’, which we suspect was due to large differences in average temperature among the three trials that resulted in a high variation in the rate of loosening. The rate of loosening of fruit with low initial FDF (lower confidence limit) was –0.208 N/h, which was higher than the mean and upper confidence limit indicating that fruit with low initial FDF loosened more slowly.

Table 1. Variation in fruit detachment force before CMNP application for the lower and upper 99% confidence limits on each application date and for each CMNP treatment. The lower and upper 99% confidence limits were determined using a univariate analysis.

<table>
<thead>
<tr>
<th>Date applied</th>
<th>CMNP (ppm)</th>
<th>Lower 99% confidence limit</th>
<th>Upper 99% confidence limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hamlin</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19 Dec.</td>
<td>200</td>
<td>21</td>
<td>135</td>
</tr>
<tr>
<td>19 Dec.</td>
<td>300</td>
<td>22</td>
<td>105</td>
</tr>
<tr>
<td>12 Jan.</td>
<td>200</td>
<td>21</td>
<td>86</td>
</tr>
<tr>
<td>12 Jan.</td>
<td>300</td>
<td>23</td>
<td>94</td>
</tr>
<tr>
<td>21 Jan.</td>
<td>200</td>
<td>12</td>
<td>79</td>
</tr>
<tr>
<td>21 Jan.</td>
<td>300</td>
<td>7</td>
<td>86</td>
</tr>
<tr>
<td>Means</td>
<td></td>
<td>18</td>
<td>97</td>
</tr>
<tr>
<td><strong>Valencia</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Mar.</td>
<td>200</td>
<td>34</td>
<td>120</td>
</tr>
<tr>
<td>11 Mar.</td>
<td>300</td>
<td>29</td>
<td>127</td>
</tr>
<tr>
<td>30 Mar.</td>
<td>200</td>
<td>56</td>
<td>121</td>
</tr>
<tr>
<td>30 Mar.</td>
<td>300</td>
<td>46</td>
<td>125</td>
</tr>
<tr>
<td>6 Apr.</td>
<td>200</td>
<td>47</td>
<td>117</td>
</tr>
<tr>
<td>6 Apr.</td>
<td>300</td>
<td>40</td>
<td>103</td>
</tr>
<tr>
<td>Means</td>
<td></td>
<td>42</td>
<td>119</td>
</tr>
</tbody>
</table>
than with fruit with high initial FDF. The slopes were similar for the upper and lower confidence limit and the mean for ‘Valencia’ indicating that all fruit loosened at the same rate. These results indicate that the rate of loosening in ‘Hamlin’ varied based on their initial FDF but not for ‘Valencia’.

The exponential function fit the regressions for all ‘Hamlin’ trials and CMNP concentrations with regression coefficients ranging from 0.85 to 0.99 (Table 3). The regression coefficients for the ‘Valencia’ trials varied from 0.75 to 0.97 for the first two trials, but the regression coefficients were extremely low for the 6 Apr. trial because of low temperatures that kept drop well below 1% (data not shown). Commercially acceptable levels of fruit drop before harvest are currently not known for CMNP treated ‘Hamlin’ and ‘Valencia’, so fruit drops of 2% and 5% of total yield were chosen arbitrarily for illustrative purposes on describing the extent of drop after CMNP application. In all trials, fruit from the 300 ppm CMNP treatment reached 2% and 5% fruit drop earlier than the 200 ppm as expected. However, the later trial dates for both ‘Hamlin’ and ‘Valencia’ did not necessarily cause fruit to drop earlier due to the slow loosening of sweet orange as it matures.

The goal of commercial harvesting companies that utilize canopy shakers equipped with catch frames is to maximize fruit recovery as defined by the percent of the crop that lands on the catch frame and therefore does not require hand labor to be removed from the grove or fruit destroyed during the harvesting process. We can define fruit recovery (F-rec) as:

\[ F_{\text{rec}}(\%) = 100 \times \frac{F_{d}}{F_{\text{total}}} \]

where \( F_{d} \) is the yield in fruit weight or number that lands on the catch frame and \( F_{\text{total}} \) is total yield. We can define fruit lost in the harvesting process as:

\[ F_{\text{lost}}(\%) = F_{\text{total}} - (F_{\text{drop}} + F_{\text{ml}} + F_{g}) \]

where \( F_{\text{drop}} \) is fruit that drops to the ground before harvest, \( F_{\text{ml}} \) is the loss of fruit during the harvesting process including fruit that lands on the ground or destroyed by the machine, and \( F_{g} \) is fruit left in the tree after harvest and that can be removed by hand. Maximizing fruit recovery requires minimizing \( F_{\text{drop}}, F_{\text{ml}} \) and \( F_{g} \) singly or in combination.

\( F_{\text{drop}} \) is a function of the time window between CMNP application and harvest, CMNP concentration and air temperature (Malladi and Burns, 2008; Pozo et al., 2007; Yuan and Burns, 2004). The strong fit of the exponential functions to drop data indicates that this regression should be useful in developing a predictive drop tool. The constant (C) along with time after CMNP application are responsible for the curvature of the response curve. Regressions would have to be developed to calculate the constant (C) by incorporating CMNP concentration and air temperature (Burns et al., 2005). Other factors may also affect the rate of loosening and drop that may need to be considered (Ebel and Burns, 2008).

\( F_{\text{ml}} \) is fruit loss mainly related to tree architecture, machine design (such as catch frame structure), and machine settings (such as shaker frequency and tractor speed). Improvements in all of these parameters should be considered to minimize \( F_{\text{ml}} \). CMNP has been observed to reduce \( F_{\text{ml}} \) by reducing the distance fruit is projected by the force of the shaking mechanism away from the catch frame.

\( F_{g} \) is fruit left in the tree that is often removed by hand (i.e., gleaned) and is a function of the extent of loosening by CMNP, tree architecture, and machine design and settings. The extent of loosening is in part governed by FDF at the time of harvest, which we show is highly variable throughout the entire loosening process (Fig. 1). Even though CMNP loosens all fruit including those with initially high FDF, it also loosens fruit with low initial FDF and fruit will drop once the FDF drops below the weight of the fruit. In previous studies, a 50% decline in the average FDF has been considered a target for timing harvest after CMNP application (Burns et al., 2005). In the current study, the time after CMNP application that a 50% decline in FDF occurred can be extrapolated using the regressions in Fig. 1. In general, fruit with low initial FDF begin to drop before the mean FDF declines by 50%. Thus, precision CMNP application and harvest scheduling that maximizes \( F_{\text{rec}} \) will need to focus on minimizing the sum of \( F_{\text{drop}} \) and \( F_{g} \).

Table 2. Analysis of the rate of decrease in fruit detachment force (N/h) of the mean and upper and lower confidence limits for ‘Hamlin’ and ‘Valencia’.

<table>
<thead>
<tr>
<th>Application date</th>
<th>CMNP (ppm)</th>
<th>Constant in exponential function</th>
<th>R²</th>
<th>Hours after treatment 2%</th>
<th>5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 Dec.</td>
<td>200</td>
<td>0.0294</td>
<td>0.99</td>
<td>24</td>
<td>55</td>
</tr>
<tr>
<td>12 Jan.</td>
<td>300</td>
<td>0.0361</td>
<td>0.98</td>
<td>19</td>
<td>45</td>
</tr>
<tr>
<td>11 Mar.</td>
<td>200</td>
<td>0.0227</td>
<td>0.75</td>
<td>31</td>
<td>71</td>
</tr>
<tr>
<td>30 Mar.</td>
<td>300</td>
<td>0.0239</td>
<td>0.92</td>
<td>20</td>
<td>47</td>
</tr>
</tbody>
</table>

Table 3. Exponential functions (fruit drop (%) = e(χ*hat) where hat = hours after treatment) and the hours where 2% and 5% fruit drop occurred after CMNP treatment in the various ‘Hamlin’ and ‘Valencia’ trials.
In summary, we demonstrated that there was high variation in FDF throughout the 5-d loosening period for ‘Hamlin’ and ‘Valencia’. We also demonstrated that CMNP loosened all fruit uniformly throughout the canopy, except for ‘Hamlin’ fruit with low initial FDF where fruit loosened more slowly. We found that an exponential function provided an excellent fit to the percent of fruit drop when temperatures were not so low that loosening and drop were inhibited. We propose using the exponential function to develop a predictive tool for scheduling CMNP applications and harvest with canopy shakers with catch frames by incorporating CMNP concentration and air temperature in the model.

**Literature Cited**


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