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Abscission Agent Application and Canopy Shaker Frequency Effects on Mechanical Harvest Efficiency of Sweet Orange

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Abstract. This study was conducted to determine the relationship of 5-chloro-3-methyl-4-nitro-1H-pyrazole (CMNP) concentration and canopy shaker frequency on fruit detachment force, pre-harvest fruit drop, and mechanical harvesting fruit removal of 'Hamlin' and 'Valencia' sweet orange cultivars. CMNP was applied at 0, 200, and 300 mg·L⁻¹ in a carrier volume of 2806 L·ha⁻¹. Four days after CMNP application, fruit were harvested with a canopy shaker that was operated at 3.0, 3.7, and 4.3 Hz at a tractor speed of 1.6 km·h⁻¹. The experiment was repeated 3× for 'Hamlin' (December, early January, and late January) and twice for 'Valencia' (March and April) during the 2008–2009 harvest season. Fruit detachment force was reduced by at least 50% for all CMNP-treated trees compared with the untreated controls at the time of harvest and was lower for 300 mg·L⁻¹ than 200 mg·L⁻¹ on three of the five dates tested. Pre-harvest fruit drop evaluated immediately before mechanical harvesting was higher for all CMNP-treated 'Hamlin' than untreated controls at all harvest dates, whereas 300 mg·L⁻¹ application resulted in higher pre-harvest fruit drop in 'Valencia' when compared with 200 mg·L⁻¹ or the untreated controls on both application dates. CMNP-induced fruit drop was higher in 'Hamlin' than 'Valencia'. CMNP had a greater effect on fruit removal at lower canopy shaker frequencies. The interaction of total fruit weight removed was not significant on any date as a result of variability among trees in the study. These data indicate that the amount of loosening by CMNP was concentration-dependent and facilitated removal, especially with lower canopy shaker frequencies. Development of viable commercial practices should use the percent of the total crop harvested and not the actual weight of fruit removed in determining efficacy of CMNP and harvest efficiency of the mechanical harvesters.

Of the 193,000 ha of sweet oranges [*Citrus sinensis* (L.) Osbeck] grown commercially for juice in Florida (Anonymous, 2008), 12,153 ha

or ≈7% are mechanically harvested (Florida Department of Citrus, 2008). The most common mechanical harvesting systems use a canopy shaker composed of a vertical axis with 12 sets of free-floating tines 2 m long that radiate out from the vertical axis (Ebel et al., 2009; Whitney and Hedden, 1973). The 12 sets of tines span 3.5 m from the lowest to the highest set along its vertical axis. Where the tines connect to the vertical axis, a mechanism vibrates each set of tines independently at frequencies between 3 and 5 Hz during harvest, yet each set of tines floats freely around the axis so that as the harvester moves along a row, the tines swivel through the canopy. The vertical axis and tines can be manually moved into the tree canopy to a depth determined by the operator. Fruit are "harvested" by the vibrating mechanism causing the tines to impact fruit directly or by impacting fruit-bearing

branches. The percent of the total crop removed at any given time during the harvest period is a function of depth of placement of the shaker within the canopy, the frequency of shaking of each set of tines, tractor speed, and fruit detachment force (Whitney, 1997).

There are two kinds of canopy shakers currently used in the commercial citrus industry in Florida. "Pull-behind" canopy shakers are pulled behind a tractor and drop fruit to the ground (Whitney, 1997), which are picked up by hand laborers or pick-up machines (Bora et al., 2006; Hedden et al., 1983; Whitney, 1999). The self-propelled canopy shakers contain decks located horizontally under the shaker that can be moved perpendicular to the long axis of the machine and positioned under the canopy to catch fruit that drop during shaking. Self-propelled canopy shakers work in pairs on opposite sides of a tree row and position the decks under the tree until they meet. The two units move together down the tree row shaking both sides of each tree until the decks are full, at which point they stop and unload the fruit through a conveyor into the bed of a truck that remove the fruit from the grove.

There are no abscission agents that are currently registered for use on sweet oranges that would aid mechanical harvesting. An effective abscission agent would enhance predictability and removal of sweet oranges, which is currently a limitation of mechanical harvesters (Whitney, 1975, 2000, 2003; Whitney et al., 2000a, 2000b, 2001). An abscission agent would be especially useful during late-season harvesting of 'Valencia', in which mechanical harvesting has to be ended early as a result of excessive removal of the newly developing immature fruit (Burns et al., 2006b). Furthermore, an abscission agent would allow lower harvester settings that would presumably reduce canopy injury (Baker et al., 2004; Li and Syvertsen, 2004; Whitney, 2003). Canopy injury has led commercial growers to express concerns about long-term productivity, although research has shown that properly managed trees show no long-term reductions in yield or tree mortality (Hedden and Coppock, 1968; Li and Syvertsen, 2005; Li et al., 2006; Whitney et al., 1986; Yuan et al., 2005).

A commercial label for the abscission agent 5-chloro-3-methyl-4-nitro-1H-pyrazole (CMNP) is being actively pursued by the commercial citrus industry in Florida. CMNP has been shown to increase fruit removal and reduce the force necessary to remove the fruit (Burns et al., 2005; Ebel et al., 2009a, 2009b; Freeman and Sarooshi, 1976; Koo et al., 1999; Whitney, 1975, 1976; Whitney et al., 2000a, 2000b; Wilson, 1973). CMNP is currently being studied to understand factors that affect efficacy. Research has shown that CMNP efficacy is largely a function of concentration, coverage, post-spray precipitation, and air temperature (Alferez et al., 2005; BenSalem et al., 2001; Burns et al., 2006a; Ebel and Burns, 2008; Farooq et al., 2003; Kender and Hartmond, 1999; Koo et al., 1999, 2000; Salyani et al., 2002). CMNP efficacy is

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especially sensitive to temperature, with 15.6 °C considered a critical minimum (Ebel and Burns, 2008; Yuan and Burns, 2004).

This study was conducted to determine the relationship of CMNP concentration and cycling frequency of canopy shakers on harvest efficiency of 'Hamlin' and 'Valencia' sweet orange. The study was conducted on multiple dates for each cultivar but with climate conditions and CMNP application and canopy shaker frequency treatments standardized.

Materials and Methods

Plant material and culture. Five trials were conducted on fully mature, sweet orange [*Citrus sinensis* (L.) Osbeck] trees during the 2008–2009 harvest season. The trials were conducted in commercial groves that used standard cultural practices. Cultivar, rootstock, grove location, soil type, and spray dates varied for the five trials (Table 1). The study was conducted in the Flatwoods region of southern Florida. Citrus trees in this region are generally shallow-rooted (≈45 cm) as a result of root pruning by flooding during the rainy season (mid-May to mid-October). The dry season requires daily irrigation, which is usually provided by microsprinkler irrigation.

Treatments. Trees were sprayed with a multihead air-blast sprayer (model T1000; OXBO International, Clear Lake, WI), a vertical 5.5-m boom oriented parallel to and arched over the outer part of the canopy (Ebel et al., 2009a, 2009b). Each boom had six equally spaced fan/nozzle assemblies and each fan assembly had eight Conejet #12 nozzles (Spraying Systems Co., Wheaton, IL) operating at 16.2 MPa·cm⁻². The tractor speed during application was 1.6 km·h⁻¹. The sprayer was calibrated immediately before CMNP application for every trial. CMNP (17% a.i.) was applied at 0, 200, and 300 mg·L⁻¹ in a volume of 2806 L·ha⁻¹ with 0.55 mg·L⁻¹ of the adjuvant Activator 90 (alkylphenol ethoxylate, alcohol ethoxylate, and tall oil fatty acid; Loveland Products, Inc., Greeley, CO). Dates for applications were made based on air temperatures being generally above 15.6 °C

and no precipitation forecasted for the first 24 h after application, the critical time period in which efficacy has been shown to be affected (Kossuth et al., 1978). All sprays occurred between 1300 and 1600 hr.

Four d after CMNP application, the trees in each trial were mechanically harvested using a pull-behind canopy shaker (model 3210; OXBO International). The shaker cycle frequencies used were 3.0, 3.7, and 4.3 Hz. The tractor speed during harvest was 1.6 km·h⁻¹.

Data collected. Before harvest, fruit detachment force (FDF) was determined from 10 randomly selected fruit per plot. FDF was measured using a force gauge (Force One digital force gauge; Wagner Instruments, Greenwich, CT) as described previously (Poza et al., 2004).

Fruit beneath each tree (pre-harvest fruit drop) were collected and the total weight determined. Fruit harvested by machine were collected into commercial bins that held ≈450 kg of fruit and weighed on a 5.6-t capacity, 1.2 × 1.2-m electronic floor scale (Gator Deck; Avery Weigh-Tronix, Livonia, MI). Fruit remaining in the canopy after shaking were removed by hand and weighed.

Total yield was determined by adding the weights of the pre-harvest drop fruit, the fruit dropped to the ground by the mechanical harvester, and the fruit gleaned. The percent removed was the sum of pre-harvest fruit drop and mechanically harvested fruit.

Statistical analysis. All trials were conducted as a randomized complete block design with four blocks and three adjacent trees per plot. There were at least two buffer trees between plots and a buffer row between treatment rows. Within each block was a split plot with canopy shaker setting as the main plot and CMNP treatment as the split plot. Data were analyzed using the General Linear Models procedure of the Statistical Analysis System (SAS Institute Inc., Cary, NC). Where interactions were not significant, means were separated using Duncan's multiple range test. Because FDF and the percent of total yield that dropped to the ground occurred before the trees were harvested, these data were analyzed

as a randomized complete block design with 12 blocks.

Results and Discussion

CMNP application dates were chosen using weather forecasts that predicted air temperature would be above 15.6 °C and no precipitation forecasted for the first 24 h after application; nevertheless, air temperature dipped slightly below 15.6 °C at night during the first four trials (Fig. 1). Air temperature is going to be a major consideration in scheduling commercial CMNP applications because temperatures often fall below 15.6 °C during winter (Fig. 2), the temperature below which fruit loosening slows (Yuan and Burns, 2004). Modeling the interaction of temperature and CMNP application on the rate of loosening would enhance scheduling of mechanical harvesting (Ebel and Burns, 2008).

FDF on the day of harvest was reduced by at least 50% in all trials with the reduction significantly greater at 300 mg·L⁻¹ than 200 mg·L⁻¹ on three of the five dates (Fig. 3). For the 'Hamlin' trials, FDF of the controls was ≈65 N for the December and early January trial but 39 N for the late January harvest, indicating that natural loosening would have to be considered for optimizing CMNP applications. FDF of the controls was close to 80 N for both 'Valencia' trials. The difference in FDF between these two cultivars suggests that 'Hamlin' would be more efficiently removed at a given CMNP concentration than 'Valencia'.

CMNP at 300 mg·L⁻¹ increased pre-harvest fruit drop compared with the controls in all trials (Fig. 4). Pre-harvest fruit drop was higher after treatment with CMNP at 200 mg·L⁻¹ compared with the controls in only the 'Hamlin' trials. CMNP promoted higher fruit drop in 'Hamlin' in the late January trial compared with the earlier trials as a result of over-maturation that led to lower FDF. These results demonstrate the importance of knowing the relative state of maturation as shown by FDF in determining CMNP concentration to apply.

Table 1. Cultivar, rootstock, grove, and environmental conditions during spray application of CMNP for each trial.

Tree characteristics						Spray information				
Cultivar	Rootstock ^z	Spacing (m)	Age (years)	Ht (m)	Skirt ^y (m)	Trial location	Soil classification	Date of application	Air temperature (°C)	RH (%)
Hamlin	Carrizo	3.7 × 7.8	21	4.6	0.5	Lat. 26°20'05' N Long. 81°22'22' W	Immokalee fine sand (siliceous, hyperthermic Arenic Alaquods)	8 Dec. 2008	22.7–28.7	49–51
	Swingle citrumelo	3.4 × 6.7	17	4.0	1.0	Lat. 26°23'15' N Long. 81°23'49' W	Ft. Drum (siliceous, hyperthermic Aeric Endoaquepts) and Malabar Fine Sand (siliceous, hyperthermic Grossarenic Endoaqualfs)	5 Jan. 2009	26.5–29.2	54–60
	Swingle citrumelo	3.4 × 6.7	17	4.1	0.9	Lat. 26°23'15' N Long. 81°23'49' W	Ft. Drum (siliceous, hyperthermic Aeric Endoaquepts) and Malabar fine sand (siliceous, hyperthermic Grossarenic Endoaqualfs)	26 Jan. 2009	25.2–27.5	44–48
Valencia	Carrizo	3.7 × 7.6	21	5.1	0.4	Lat. 26°19'39' N Long. 81°22'10' W	Wabasso fine sand (siliceous, active, hyperthermic Alfic Alaquods)	20 Mar. 2009	25.6–28.7	39–48
	Carrizo	3.7 × 7.6	21	4.7	0.4	Lat. 26°19'39' N Long. 81°22'10' W	Wabasso fine sand (siliceous, active, hyperthermic Alfic Alaquods)	14 Apr. 2009	27.5–31.7	41–60

^zCarrizo citrange [*C. sinensis* × *Poncirus trifoliata* (L.) Raf.], Swingle citrumelo (*Citrus paradisi* × *Poncirus trifoliata*).

^yHeight of the lowest branches from the soil line.

RH = relative humidity.

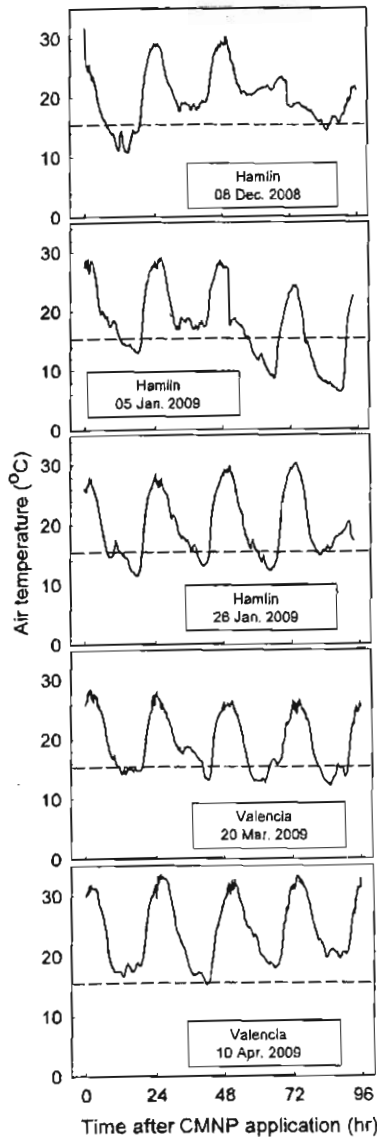


Fig. 1. Air temperature from the time of application through harvest for the five trials conducted in this study. The horizontal line at 15.6 °C indicates the temperature below which the rate of loosening by CMNP declines resulting from low air temperature.

Fruit drop is a minor concern with pull-behind canopy shakers because the sweepers in front of the tires reduce the number of fruit that get crushed, and all fruit ends up being picked up manually whether they drop naturally or are harvested by the machine. On the other hand, pre-harvest fruit drop is a major concern with self-propelled machines because its efficiency relies on fruit capture on the catch frame and thus minimizing the requirement for hand labor. Because the shaking mechanism of both types of machines is the same, the data in this study can be extended to self-propelled machines. For self-propelled machines, it would be most desirable to mechanically harvest before significant drop occurs. In this study, the greater drop for 'Hamlin' than 'Valencia'

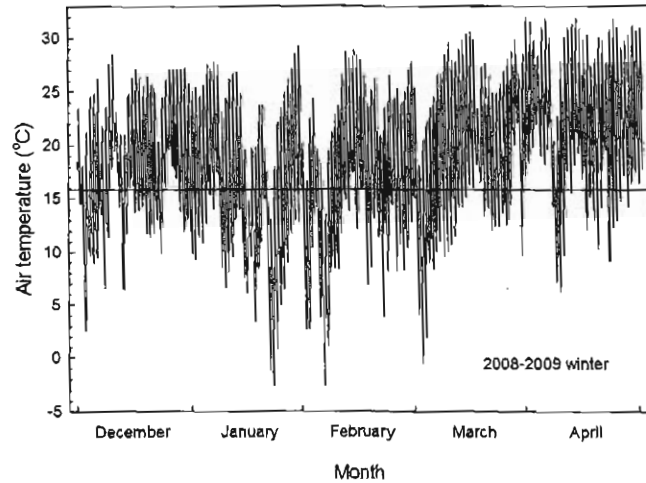


Fig. 2. Air temperature from 1 Dec. through 30 Apr. during the 2008–2009 winter. Air temperature was measured every 5 s at 2-m height and the average across every 15 min was stored by a weather station in Immokalee, FL (Florida Agricultural Weather Network). The horizontal line at 15.6 °C indicates the temperature below which fruit loosening by CMNP is inhibited.

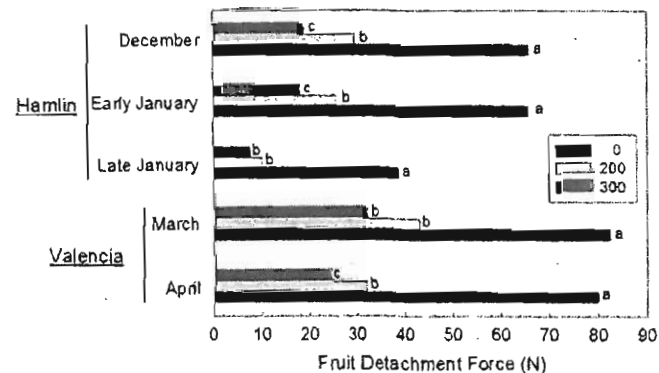


Fig. 3. Fruit detachment force four days after spraying with CMNP at 0, 200, and 300 L·ha⁻¹ and immediately before harvesting with a canopy shaker. Different letters within each sampling date indicate significant differences ($P < 0.05$).

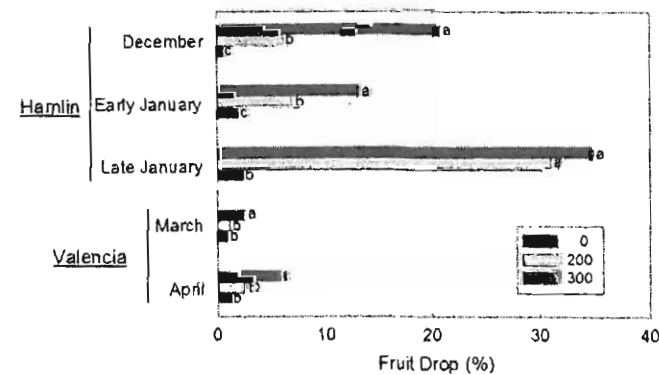


Fig. 4. Pre-harvest fruit drop percentage four days after CMNP application at 0, 200, and 300 mg·L⁻¹ and before harvesting with a canopy shaker. Different letters within each sampling date indicate significant differences ($P < 0.05$).

would indicate that waiting 4 d after spray application under the conditions CMNP was applied in this study would be too long for self-propelled machines. However, drop for 'Valencia' was under 6% for all treatments,

indicating that waiting 4 d after spray may be closer to the desired time for this cultivar for March and April assuming similar temperature conditions as in this study. More work must be done to identify application

Table 2. Statistical analysis ($P > F$) of machine harvest (canopy shaker) frequency and CMNP application on percent fruit removal (pre-harvest drop plus fruit removed by the canopy shaker) for each trial.^a

Significance	Hamlin			Valencia	
	December	Early January	Late January	March	April
Harvester × CMNP	<0.0001	0.0001	<0.0001	0.0213	0.0951
CMNP	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Harvester × block	0.0047	0.0085	0.0889	0.1667	0.4187
Harvester	0.0005	0.0078	0.0047	0.0003	0.0003
Block	0.2796	0.7008	0.8871	0.8501	0.1236

^aThe harvester term reflects different tine frequencies used during fruit harvesting (3.0, 3.7, and 4.3 Hz), whereas the CMNP term reflects different a.i. concentrations applied (0, 200, and 300 mg·L⁻¹).

Table 3. Statistical analysis ($P > F$) of fruit weight (kg) removed by CMNP and mechanical harvester (canopy shaker) frequency treatments with removal including pre-harvest fruit drop plus fruit harvested by the canopy shaker.

Significance	Hamlin			Valencia	
	December	Early January	Late January	March	April
Harvester × CMNP	0.8072	0.1433	0.6588	0.3748	0.6727
CMNP	0.1123	0.0653	0.5584	0.0165	0.0198
Harvester × block	0.8072	0.0717	0.0305	0.7197	0.6727
Harvester	0.1919	0.9232	0.1590	0.0002	0.0180
Block	0.2823	0.3986	0.7446	0.3224	0.0735
Main effect means					
CMNP (mg·L ⁻¹)					
0	218 b	108 ab	118	94 b	100 b
200	236 ab	119 a	126	106 ab	119 a
300	257 a	105 b	119	115 a	116 a
Harvester frequency (Hz)					
3.0	218	110	103	77 c	95 a
3.7	246	110	132	111 b	114 a
4.3	248	113	128	126 a	125 a

Different letters within columns and main effect means indicate significance at $P < 0.05$.

conditions that would enable maximum machine removal with minimal loss of fruit to pre-harvest drop.

For all trials, the percent fruit removal was calculated based on the weight of pre-harvest drop fruit plus the weight of fruit removed by the pull-behind canopy harvest machine. In cases in which CMNP was applied, the percent fruit removal reflected the weight of fruit removed by the interaction of CMNP and the harvest machine. There were significant interactions between CMNP concentration and canopy shaker frequency ($P < 0.05$), although the interaction was significant at the $P = 0.0951$ for the April 'Valencia' trial (Table 2). The beneficial effects of CMNP were greater at lower canopy shaker frequency in all trials (Fig. 5), results of which are supported by an earlier study (Burns et al., 2005). The fruit remaining in the tree after machine harvest was generally closer to the trunk than the periphery and higher in the canopy (Burns et al., 2006; data not shown). The 12 sets of tines span a total of 3.5 m along the vertical axis, yet the distance between the skirt and highest part of the tree was as much as 4.7 m. Although the tines did not reach the entire canopy, most fruit near the top and the bottom of the canopy were still removed as a result of the harvesting action promoted by canopy agitation. These trees were fully mature and the height typical of trees in the citrus industry in Florida.

In the current study, trees were selected based on their uniformity within the grove. Even with this intentional uniformity, the

variation was such that the interaction between CMNP and harvester frequency on the actual weight of fruit removed was not significant in any trial, even at the $P < 0.1$ level of significance (Table 3). Furthermore, the CMNP main effect was only significant for the early January 'Hamlin' trial ($P = 0.0653$) and both 'Valencia' trials, which were $P = 0.0165$ and $P = 0.0198$ for the March and April trials, respectively. In general, trees sprayed with higher CMNP concentrations had higher fruit removal. Harvester frequency main effect was also only significant for the 'Valencia' trials with $P = 0.0002$ and $P = 0.0180$ for the March and April trials, respectively. In general, higher harvester frequency removed more fruit, but the differences between CMNP-treated and untreated fruit removal was less as shaker frequency increased (Fig. 5).

A commercial label is being actively pursued for CMNP as an aid to mechanical harvesting of sweet oranges in Florida. Assuming successful registration, it is our goal to establish protocols for CMNP adoption by the Florida citrus industry. The data in this study provide a framework by how much CMNP will improve harvest efficiency for 'Hamlin' and 'Valencia' from December through April. The data have direct application to pull-behind canopy shakers, but the pre-harvest drop of 'Hamlin' was excessive for self-propelled machines. Additional work needs to be conducted to determine the interaction of CMNP application and mechanical harvester on percent fruit drop and removal over time to optimize harvest efficiency.

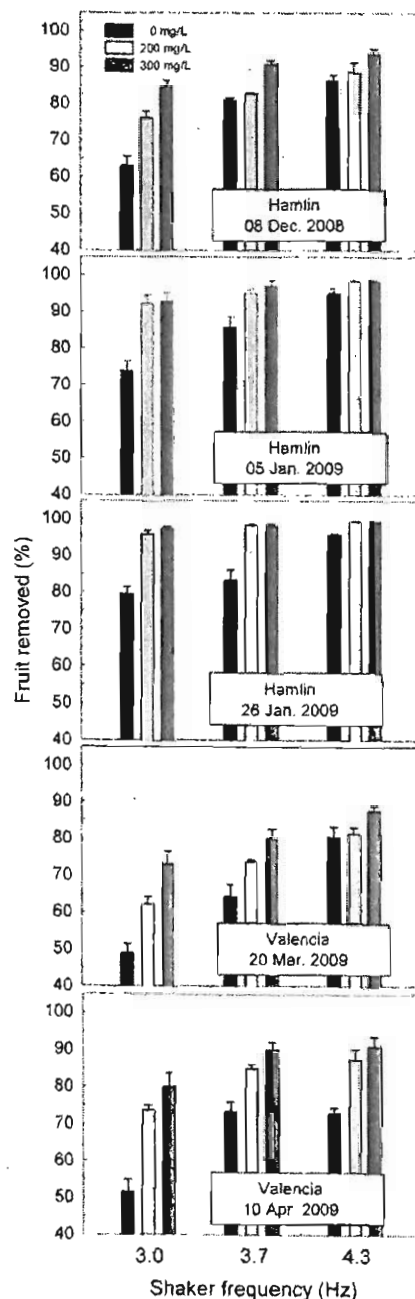


Fig. 5. Interaction of CMNP treatment and canopy shaker frequency on the percent of total yield removed on five different dates for 'Hamlin' and 'Valencia' sweet orange. Vertical bars are 2× the SE of the mean.

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