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Incorporation of Air Temperature into a Model That Predicts Loosening of Sweet Oranges by the Abscission Agent CMNP

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CMNP (5-chloro-3-methyl-4-nitro-1*H*-pyrazole) is an abscission agent that is in the process of being labeled as an aid for mechanical harvesting. A mathematical model that incorporates the most important factors affecting CMNP efficacy may be a useful tool for mechanical harvesting companies and growers to schedule abscission sprays and harvests. Previous research has demonstrated that two of the most important factors include CMNP concentration and temperature. Using data from previous research, we developed a model using concentration and air temperature and applied it to 18 treatments from 5 studies that included 10 treatments for 'Hamlin' and 8 treatments for 'Valencia'. Inputs into the model included CMNP concentration, hourly air temperature from time of application to harvest, and fruit detachment force (FDF) at time of application. The model calculated a predicted FDF at time of harvest, which was compared to actual FDF. The average FDF for the 18 treatments at time of application was 92 N. The average FDF at harvest was 51 N and the average predicted FDF was 58 N. Thus, the difference between actual and predicted FDF was about 13%. However, there was considerable variation among treatments, with the range in difference between actual and predicted FDF from –40 to 57 N. There was no difference between cultivars in predictability of the model. Factors causing this high variation between predicted and actual FDF at harvest will need to be included in the model before it will be commercial viable.

There are currently 14,400 ha of sweet oranges mechanically harvested (http://citrusmh.ifas.ufl.edu) of the total 193,000 ha in Florida (Bronson, 2007). Mechanically harvested acreage is not higher partly due to concerns by growers that the level of injury to the canopies of the trees by the mechanical harvesters may reduce long-term productivity. Abscission agents that reduce the force necessary to remove the fruit may allow reduced harvesting intensity, and therefore lower the extent of injury by the machines. Abscission agents that allow for lower energy is especially important for late-season 'Valencia' to reduce removal of the next year's young developing crop (Burns et al., 2006).

CMNP has been shown to be a highly effective fruit-loosening agent of sweet oranges by promoting formation of the abscission layer (Burns et al., 2005). Other chemicals have been tested as abscission agents, but none have proven as effective as CMNP. Because of its effectiveness, CMNP is in the process of being labeled as an aid for mechanical harvesting of oranges for processing into juice.

A considerable amount of research has been conducted since the first report on CMNP for loosening sweet oranges (Wilson, 1973). Studies conducted to date have identified many factors that affect abscission agent efficacy besides CMNP concentration (Burns et al., 2005). Plant factors that may affect loosening include cultivar, rootstock, stage of crop maturity, and tree health (Biggs and Kossuth, 1980; Hartmond et al., 2000; Yuan et al., 2001a). Climate factors that may affect efficacy include temperature, relative humidity, and precipitation during the first 8 h after application (Biggs and Kossuth, 1980; Kossuth et al., 1978, 1979; Yuan and Burns, 2004). Two of the most important factors that affect efficacy include CMNP concentration and air temperature. A mathematical model that incorporates the most important factors may be a useful tool for mechanical harvesting companies and growers to schedule abscission sprays and harvest. We have developed a preliminary model using CMNP concentration and air temperature and tested the model using published and unpublished studies. Further development and validation of the model as well as factors that will be considered for the model will be discussed.

Materials and Methods

Theoretical development of the model

Temperature. In a growth chamber experiment where temperature was carefully controlled, Yuan and Burns (2004) found a nonlinear relationship between temperature (T) and FDF 5 d (120 h) after 200 mg·L^{-1} CMNP was applied to 'Hamlin' orange. FDF of untreated fruit increased slightly with temperature with the change over temperature described by a linear equation. By subtracting FDF of the treated fruit from FDF of the control at each temperature and dividing the quantity by the total elapsed time, we can derive a rate of decrease in FDF over time (FDF/h) at any T as:

$$\text{FDF/h} = [\text{FDF(control)} - \text{FDF(CMNP treated)}]/\text{time}$$

$$\text{FDF/h} = [(0.1003T + 89.2393) - (15.3557 + 71.121/(1+e^{((T - 18.2074)/1.2948)})^{0.9383})]/120 \quad \text{Eq. 1}$$

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The experiment to derive the equations above was conducted between T of 10 to 26.7 °C. Because the nonlinear regression for treated fruit were asymptotic at both extremes, estimations beyond these temperature limits are acceptable. Furthermore, estimations beyond the temperature limits should be rare since actual temperatures in southern Florida where most mechanical harvesting is conducted only occasionally exceed these limits.

CMNP concentration. Burns et al. (2005) found a linear response in CMNP concentration on FDF between 0 to 250 $mg \cdot L^{-1}$, 5 d (120 h) after treatment for 'Hamlin' orange on Carrizo citrange [*C. sinensis* x *Poncirus trifoliata* (L.) Raf.] rootstock. By assuming that the effect of CMNP is proportional across the entire range of temperatures, we can modify Equation 1 by multiplying by the CMNP concentration divided by 200, which was the concentration of CMNP applied in the study used to derive Equation 1:

$$FDF/h = (CMNP/200) \times [(0.1003T + 89.2393) - (15.3557 + 71.121/(1 + e^{((T - 18.2074)/1.2948))^{0.9383}})]/120 \quad \text{Eq. 2}$$

T at time of application was 81.7 °F (27.6 °C) and dropped to 57.9 °F (14.4 °C) at night and so some error may be introduced since we cannot factor in the effects of temperature on FDF response in this particular study.

Equation 2 can be simplified to:

$$FDF/h = CMNP \times [(4.18 \times 10^{-6}T) - (0.0029 \times (1+e^{((T - 18.2074)/1.2948))^{0.9383}}) - 0.00308] \quad \text{Eq. 3}$$

Test of the model using published and unpublished data

The model was tested by first, finding published and unpublished studies for sweet oranges in Florida that included the CMNP concentration applied in the test, the year, dates and location of the test, and the FDF at the time of spray and at the time of harvest. Second, hourly air temperatures from the time of spray to the time of harvest were extracted from the Florida Agriculture Weather Network for weather stations nearest the experimental site. Third, air temperature and CMNP concentration for each study was inputted into the model to determine the predicted FDF at harvest. Finally, the predicted FDF was compared to the actual FDF.

Statistical analysis. The data were analyzed as a completely randomized design. To determine the ability of the model to predict actual FDF, the independent variable was predicted FDF and the dependent variable was actual FDF. Cultivar was included in the model as a discrete variable.

Results and Discussion

The 18 treatments from the 5 studies represented a wide range of temperature conditions due to the various times of year the data were collected. Air temperatures varied from study to study sufficiently such that some treatments demonstrated very little loosening because of low air temperatures, and some treatments demonstrated high loosening because most hourly temperatures were at or above the maximum temperature for loosening (Fig. 1). The impact by the wide range of temperatures is illustrated

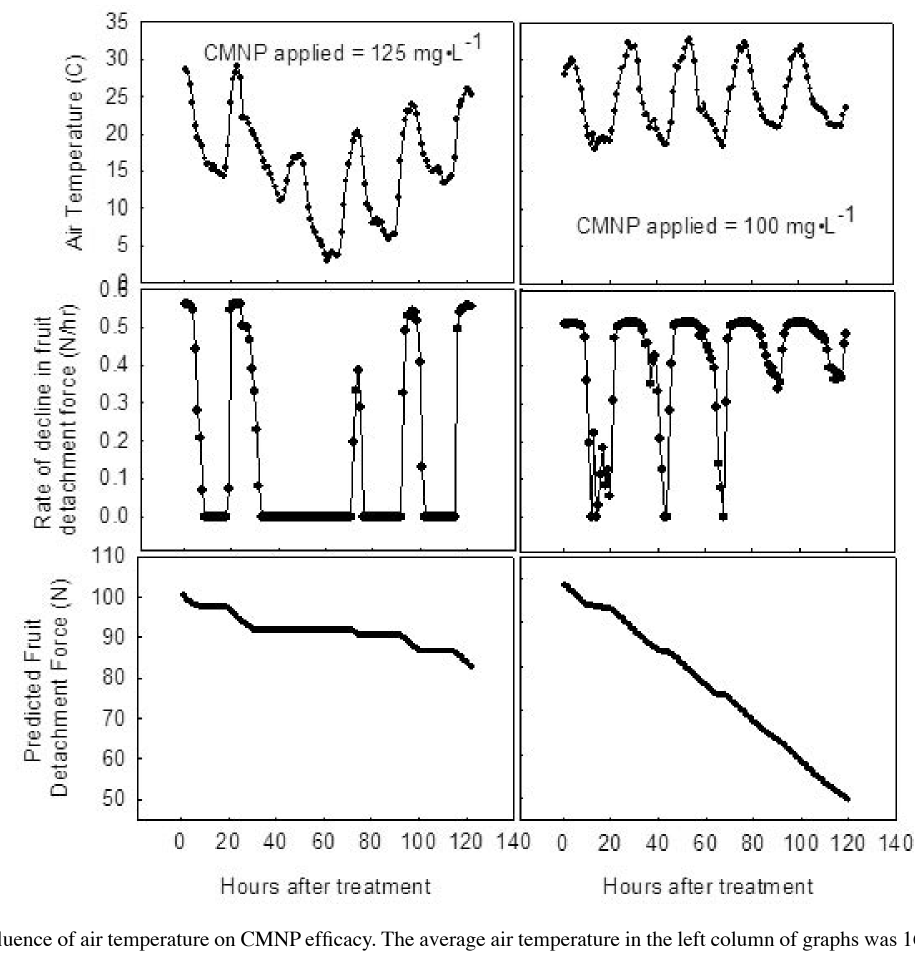

Fig. 1. Examples of the influence of air temperature on CMNP efficacy. The average air temperature in the left column of graphs was 16 °C (Burns et al., 2005) and the right column of graphs was 25 °C (Whitney et al., 2000).

by large difference in rate of decline in predicted FDF. In all studies and treatments, there were at least some hours below the maximum threshold for CMNP loosening. For example, the column of graphs on the right was one of the maximum average air temperatures that occurred in this study (average air temperature = 25 °C) and yet air temperature during three nights was low enough to decrease the rate of loosening to zero N/h. One limitation of this study was the lack of temperature sensors at the experimental sites. The FAWN weather stations were within 2 to 5 km of each site, which probably introduced some error in temperatures used in the model. Nevertheless, the wide range of temperatures among all 18 studies allows a rigorous test of the effect of air temperature on efficacy of CMNP.

FDF when treated with CMNP was on average lower for 'Hamlin' (FDF = 80 N) than 'Valencia' (FDF = 106 N; Table 1). CMNP application reduced FDF to an average of 45 N for 'Hamlin' and 58 N for 'Valencia', whereas the average predicted FDF was 44 N for 'Hamlin' and 76 N for 'Valencia'. The difference between actual and predicted FDF was –1 N for 'Hamlin' and 17 N for 'Valencia'. Over all 18 treatments, the average actual FDF was 51 N, the predicted FDF was 58 N so the difference between actual and predicted was 7 N or about 13%. Although the difference between actual and predicted FDF was low, the variation among studies was very high. The range in the difference between actual and predicted FDF was –40 N to 57 N. The variation was confirmed with the ANOVA with the total $R^2 = 0.22$ and the coefficient of variation at 43%. As noted very early after the introduction of CMNP, the high grove-to-grove variation in CMNP efficacy was a major concern (Wilson, 1973).

In order to be commercially viable, other factors that affect abscission by CMNP will need to be identified and included in the model. Although this study included two cultivars, the ANOVA indicated no difference between them. However, other studies need to be evaluated to conclusively eliminate cultivar as an important factor in the model. Rootstock may have an effect, but in the studies by Burns et al. (2005), Ebel (unpublished), and Ebel and Morgan (unpublished), only Carrizo citrange were used, and the rootstock was not listed in the other studies. Therefore, no conclusion can be drawn from these data concerning the influence of rootstock on CMNP efficacy.

Stage of crop development is important for efficacy of CMNP, at least with late season 'Valencia' during the "less-responsive period" in early May (Hartmond et al., 2000; Yuan et al., 2001). In the current study, however, no clear pattern emerged that indicated less responsiveness to CMNP. For example, the two 1 May treatments had predicted FDF lower than actual (–8 and –19 N) as would be expected, but the 18 May treatments had predicted FDF higher than actual (22 and 42 N), which would not be expected. The 1 May and 18 May treatments would have occurred within the "less-responsive period," which lasts 4 to 8 weeks (Hartmond et al., 2000) and spans from at least the last week of April through the third week of May (Yuan et al., 2001b). Other conditions may have interacted with fruit responsiveness to mask the less responsive period, but those factors are currently unknown.

Post-application precipitation is especially important in efficacy of CMNP application. Rain during the first 8 h after application caused 70% or more of the CMNP to be removed from the peel (Kossuth et al., 1978). In the unpublished study by Ebel (Table 1), precipitation occurred after application, which may explain

Table 1. Results of the model with CMNP concentration and hourly air temperature as inputs.

CMNP application			Harvest				
Date	Concn ($mg \cdot L^{-1}$)	FDF when treated (N)	Date	Actual FDF (N	Predicted FDF (N)	Difference between actual and predicted (N)	Source
				Hamlin			
4 Dec.	125	108	9 Dec.	76	90	14	Burns et al., 2005
4 Dec.	250	108	9 Dec.	45	66	21	Burns et al., 2005
8 Feb.	200	58	12 Feb.	34	23	-11	Ebel and Morgan, unpublished
12 Dec.	200	77	17 Dec.	59	19	-40	Ebel, unpublished
12 Dec.	300	79	17 Dec.	53	10	-43	Ebel, unpublished
14 Dec.	200	67	17 Dec.	52	33	-19	Ebel, unpublished
14 Dec.	300	85	17 Dec.	51	45	-6	Ebel, unpublished
6 Jan.	100	76	16 Jan.	43	35	-8	Whitney et al., 2000
20 Jan.	100	85	30 Jan.	13	70	57	Whitney et al., 2000
6 Feb.	100	61	13 Feb.	24	51	27	Whitney et al., 2000
Hamlin average		80		45	44	-1	
				Valencia			
25 Mar.	125	124	29 Mar.	74	96	22	Burns et al., 2005
25 Mar.	250	124	29 Mar.	60	79	19	Burns et al., 2005
15-Apr	50	99	20-Apr	49	81	32	Whitney et al., 2000
15-Apr	100	99	20-Apr	21	49	28	Whitney et al., 2000
1-May	50	101	7-May	92	84	-8	Whitney et al., 2000
1-May	100	101	7-May	76	57	-19	Whitney et al., 2000
18-May	50	101	21-May	66	88	22	Whitney et al., 2000
18-May	100	101	21-May	28	70	42	Whitney et al., 2000
Valencia average		106		58	76	17	
Overall average		92		51	58	7	

the lack of loosening by CMNP as predicted by the model. However, the amount of precipitation was not recorded at the experimental site so we cannot be certain if sufficient rain fell to affect CMNP uptake.

Although the model on average predicted reasonably well CMNP efficacy on loosening sweet oranges, the high variability among treatments and studies indicates that more factors will need to be included in the model before it will have commercial utility. Several factors affecting efficacy were discussed above, but other factors not listed that may affect loosening include tree health and its effect on fruit sensitivity to CMNP, volume of CMNP applied (to calculate g a.i./ha), drying rate, and factors affecting uptake rate and metabolism. We are currently evaluating empirical adjustments to the model for these factors to improve model predictability.

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