OPTIMIZATION OF COPPER FUNGICIDE APPLICATION TIMING FOR CITRUS GROVES IN FLORIDA

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my family and everyone else who have helped me be the better person I am today

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Copper fungicides are commonly used for protective applications against foliar fungal and bacterial diseases in citrus groves. Management of these products must be finely balanced between disease prevention, application costs, fruit blemishes caused by copper phytotoxicity, and toxic accumulation of copper in the soil. The traditional schedule for copper sprays in Florida is an every 21-day post-bloom application. However, our computer simulation analysis showed that this traditional schedule is inefficient; it leaves the grove unprotected in wet years and applies unnecessary copper sprays in dry years. In order to facilitate the copper management for citrus growers, a user-friendly internet-based decision support system was developed. This system is capable of estimating the copper residue on the fruit based on rainfall records and spray details. This information allows producers to plan the copper applications in order to minimize unprotected periods while avoiding unnecessary applications in dry years. For growers who are distant from weather stations or that cannot quickly adjust their schedules according to the web tool recommendations, we developed a schedule with varying application intervals or spray concentrations. These schedules were calculated

with the objective of minimizing the number of unprotected days according to historic weather data.

CHAPTER 1
INTRODUCTION

Copper (Cu) compounds are the most widely used fungicides or bactericides in Florida citrus for the management of foliar diseases (Albrigo et al., 2005; Graham et al., 2010; Graham et al., 2011). Traditionally, copper fungicides have been used to manage diseases such as melanose (caused by *Diaporthe citri*), Alternaria brown spot (caused by *Alternaria alternata*), citrus scab (caused by *Elsinoë fawcettii*) and greasy spot rind blotch (caused by *Mycosphaerella citri*) (Dewdney et al., 2012a). Particularly for melanose, sufficient copper residue must be present to protect fruit from petal fall until mid-July, when the fruits are no longer susceptible to these diseases (Albrigo et al., 2005). More recently, two new diseases were introduced to Florida; Asian citrus canker, caused by the bacterium *Xanthomonas citri* subsp. *citri* and citrus black spot, caused by the fungus *Guignardia citricarpa* (Spann, T.M., 2008; Schubert et al., 2012). Copper applications are an essential part of the management programs for these diseases (Schutte et al., 1997; Graham et al., 2010; Graham et al., 2011; Dewdney et al., 2012a; Dewdney et al., 2012b). However, citrus is susceptible to black spot and citrus canker until September and October, respectively, and not much is known about how copper residue decay is affected by the high summer rainfall common in Florida.

Copper, as any agricultural input, has to be correctly dimensioned. If the concentration of copper is too high, it can frequently cause or accentuate market-value reducing blemishes due to copper stippling (phytotoxic burn) from excessive copper ion uptake by the fruit rind cells, especially at temperatures above 34.5°C (Schutte et al., 1997; Timmer and Zitko, 1998). Furthermore, toxic levels of copper can build-up in soil due to multiple, high concentration applications of copper over many years (Alva et al., 1993; Graham et al., 1986). In older groves where copper has been used for many years, the soil can contain up to 370 kg ha-1 metallic copper (Timmer and Zitko, 1996). High copper concentrations in the soil can slow growth, thin canopies, darken fibrous roots and cause foliar iron deficiency, particularly on acid soils (Alva et al., 1993; Graham et al., 1986). Historically, it was recommended to use one or two applications of 9 kg ha-1 metallic copper for foliar disease management (Timmer and Zitko, 1996). It was shown that lower rates of copper fungicides could give the same disease management efficacy as the higher rates (Timmer et al., 1998) and that splitting the applications, without increasing the total copper used per year improved disease management (Timmer and Zitko, 1998). These findings and other studies were used to better understand the behavior of copper as a fungicide or bactericide in Florida citrus groves (Albrigo et al., 1997; Timmer and Zitko, 1996; Timmer et al., 1998) and to develop a copper spray scheduling recommendation system (CuSSRS) (Albrigo et al., 2005) to aid growers in scheduling copper fungicide sprays for early season disease management.

The CuSSRS was evaluated by comparing predicted residue levels to actual copper residue levels in the field. Disease severity in plots sprayed following the CuSSRS predictions were compared with a standard 21-day calendar schedule and an unsprayed treatment (Albrigo et al., 2005). The traditional 21-day schedule is the currently recommended application schedule (Dewdney and Graham, 2012) and is commonly used by Florida citrus growers, especially for melanose and/or canker management. Although the CuSSRS was shown to effectively reduce cost and improve coverage (Albrigo et al., 2005), it was not widely used by citrus growers. The reasons given by growers for not adopting the system included a confusing interface, too many inputs, difficult to install, unclear output and lack of updates. A problem in the routine which connected to the Florida Automated Weather Network (FAWN; http://fawn.ifas.ufl.edu/) for real time weather information across the state was another problem that made the copper system difficult to use. To revive this valuable tool, a project was initiated to develop a web-based version of CuSSRS with a simple and self-explanatory interface to allow growers to estimate copper residue in their groves and analyze the results without external aid. The connection between weather data and disease models is an essential step in order to enhance the contribution of these models to the producers (Guillespie and Sentelhas, 2008).

Objective

Our primary objective was to help Florida citrus growers better schedule copper applications and maximize fruit protection while reducing environmental impacts and production costs. This objective has to be fulfilled with a practical interface aiming to require the least possible time commitment from the producer.

Specific objectives included:

- To understand and review the algorithms used in the CuSSRS model and the sensitivity of the model to the various inputs.
- To translate the original CuSSRS model to the R statistical language (R Development Core Team, 2011).
- To analyze the variability of copper residue coverage using historical meteorological data for citrus producing areas in Florida and current schedule recommendations.
- Develop a practical web tool which allows producers to simulate the remaining copper residue with minimal effort.
- To analyze the potential benefits of the developed web tool based on simulations.

- Develop optimizations for the current recommendations using historical weather data.

Citrus Production in Florida

Citrus production is important to the Florida economy. During the 2010-2011 season, Florida produced more than 63% of United States citrus in a combined area of 203,799 ha for all types (USDA, 2011). Approximately 84% of the Florida citrus production is processed for juice. The estimated production value of Florida Citrus in the 2010-2011 season was US$ 1,573,116,000 which represents 52% of total citrus production value from United States (USDA, 2011). Florida Citrus production is principally located in central and southwestern Florida. Florida citrus growers in 2009-2010 produced 133.7 million boxes (40.8 kg box^{-1}) of sweet oranges, 96% being used for juice and 20.3 million boxes (38.5 kg box^{-1}) of grapefruit of which 54% were used for grapefruit juice. Other citrus types grown in Florida include specialty fruit like mandarin (tangerine) hybrids and Navel orange. The specialty fruit industry is concentrated on the Central Ridge of Florida in Lake, Orange and Polk Counties and many grapefruit plantings are on the East coast in Indian River and St. Lucie Counties (Fig. 1-1).

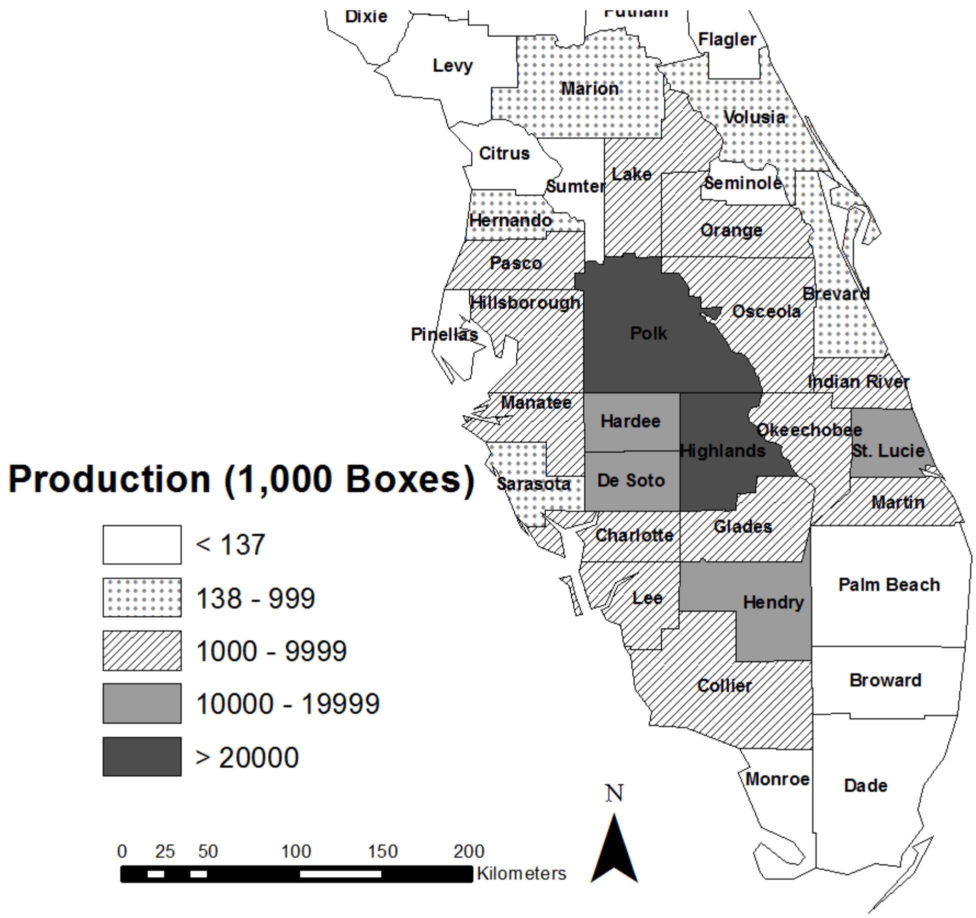

Figure 1-1. Florida citrus production by county in 2009-10 according to the Florida Department of Agriculture and Consumer Services (FDACS, 2011).

The Copper Residue Model

The CuSSRS model was created to simulate the copper residue decay on citrus fruit over time. It was developed with the Java programming language as a stand-alone application and integrated within a larger citrus planning and scheduling program called DISC (Decision Information System for Citrus) (Beck, 2006). The residual copper is calculated on a daily basis from the most recent application relying on inputted spray details and daily rainfall.

The required input information includes bloom date, cultivar, details on copper spray applications such as concentration and spray volume, fruit position, and daily rainfall data. The different copper concentrations and volumes produce dissimilar residue levels on the fruit. Fruit growth and rainfall events are used to simulate the amount of copper residue decreased by fruit surface expansion and weathering of the residue layer. The model simulates the copper residue for fruit located inside and outside of the tree canopy. The copper deposition and rainfall events affect the outer fruit more intensely than the inner fruit (Albrigo et al., 2005). Interior fruit and fruit on the top of the tree receive lower copper deposits from commonly used spray equipment. On the other hand, there is less rainfall removal of copper for interior fruit or less disease pressure for the top of the tree when considering melanose (Albrigo et al., 2005). Very low spray diluent volumes can lead to excessive deposits on exterior surfaces of outer fruit which can cause copper stippling in addition to poor disease management on interior fruit (Albrigo et al., 1997). Increasing diluent rate produced a more uniform coverage along the tree but also increased the copper lost by run-off (Albrigo et al., 1997).

The copper residue threshold for reapplication was based on the recommended values needed to provide a complete protection safety margin. CuSSRS adopts a default warning threshold of 0.5 µg cm^{-2} and a danger threshold of 0.25 µg cm^{-2}. The minimum residue in which the grove is still considered protected is 0.1 µg cm^{-2} (Albrigo et al., 2005).

Disease Management Models for Citrus

Other systems have been proposed to help citrus growers better manage diseases. The ALTER-RATER is a weather-based model with the objective of help producers correctly time fungicide sprays for Alternaria management (Bhatia, A., 2002;Timmer et al., 2001). It is based on a cumulative score, which is influenced by rainfall, leaf wetness and temperature. The system does not have a web interface and requires the producer to manually fill the weather data in a table. Also a model was developed for management of Post bloom fruit drop, caused by *Colletotrichum acutatum* (Timmer et al., 1996). This model has shown to produce accurate predictions but requires considerably more information beyond weather data.

AgroClimate

AgroClimate is a web-based climate information and decision support system (http://www.agroclimate.org) (Fraisse et al., 2006) developed to help agricultural producers reduce risks associated with climate variability in the southeastern U.S.A. (Fraisse et al., 2006). It is periodically updated and maintained to ensure up-to-date information and the simplest possible interface. A mobile version is also available when the AgroClimate website is accessed from a mobile device. It was designed and implemented by the Southeast Climate Consortium (SECC-http://seclimate.org) in partnership with the Florida Cooperative State Extension Service. The system was developed to be hosted in Linux/Unix platforms but can easily be transferred to others. The dynamic tools were developed using the PHP (Hypertext Preprocessor) web programming language, Javascript language, HTML, Cascading Style Sheets (CSS) and MySQL database (Pavan et al., 2011).

Decision support tools available in AgroClimate include: (a) Climate risk tools: expected (probabilistic) and historical climate information as well as freeze risk at the county level; (b) Crop yield tools: expected yield based on soil type, planting date, and basic management practices for corn, cotton, peanut, potato, and tomato, and historical county and regional yield databases; (c) Crop disease tools: disease risk monitoring and forecasting for anthracnose and botrytis fruit rot in strawberry, peanut leaf spot, and the citrus copper application scheduler; (d) Crop development tools: monitoring and forecasting of growing degree-days and chill accumulation; (e) Drought monitoring tools: monitoring and forecasting of the Agricultural Reference Index for Drought (ARID), Keetch-Byram (KBDI), and the Lawn and Garden (LGMI) drought indices; and (f) Footprint tools: carbon footprint of selected fruits and water footprint of cereal crops. AgroClimate provides climate forecasts and outlooks, monthly climate summaries, crop management options to mitigate climate-associated risks for pasture, forestry as well as certain crops and fruits. It also includes background information about the main drivers of climate variability and basic information about climate change in the Southeast USA.

Summary

This chapter described the objectives of this study and introduced background information about the citrus production in Florida. Traditional copper management practices and the copper model used in the simulations contained in this study were also introduced. Chapter 2 details the copper model inner equations and the methods used for the simulations. Also in Chapter 2, it is described the development process of the proposed web tool for copper residue management. Simulation results and the copper residue web-based tool are discussed in Chapter 3. Chapter 4 includes our main conclusions and recommendations for future developments.

CHAPTER 2
SYSTEM DEVELOPMENT AND SIMULATION METHODS

Understanding the Copper Model Java Source Code

Figure 2-1 shows that the first step in the extracted copper residue model was the calculation of the copper deposition provided by the first spray application. The copper residue is always zero at the beginning of the season because the previous season's fruit have been harvested by time of application in the spring. The applied copper residue depends on the fruit area available, volume and concentration of the copper suspension, and the position of the fruit, inside or outside the tree canopy (Table 2-1).

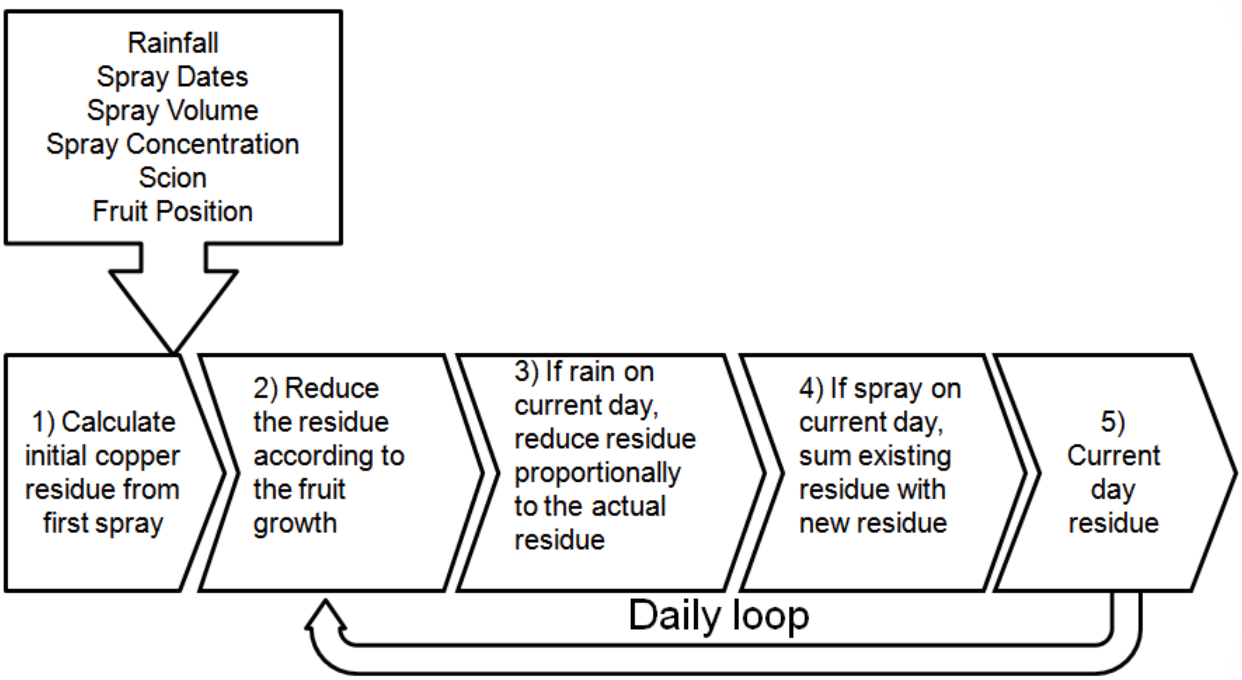

Figure 2-1. Simulation steps of the copper spray scheduling recommendation system (CuSSRS) showing the daily loop required to estimate daily copper residue levels.

Table 2-1. Copper application residue formulas extracted from the copper spray scheduling recommendation system (CuSSRS) source code.

Fruit position	Volume (L ha^{-1})	Formula to estimate copper residue[a]
Inside	<1,169	$DEPO = (0.6399 + 0.005539\,V)\,A\,(\frac{C}{4})$
Inside	>=1,169 and <=2,338	$DEPO = (8.036 - 0.001082\,\mathrm{V})\,\mathrm{A}\,(\frac{\mathrm{C}}{4})$
Inside	2,338	$DEPO = (5.357 + 0.0002101\,\mathrm{V})\,\mathrm{A}\,(\frac{\mathrm{C}}{4})$
Outside	<1,169	$DEPO = (0.5171 + 0.007656\,\mathrm{V})\,\mathrm{A}\,(\frac{\mathrm{C}}{4})$
Outside	>=1,169 and <=2,338	$DEPO = (11.61 - 0.001528\,\mathrm{V})\,\mathrm{A}\,(\frac{\mathrm{C}}{4})$
Outside	>2,338	$DEPO = (9.821 - 0.07448\,\mathrm{V})\,\mathrm{A}\,(\frac{\mathrm{C}}{4})$

[a]The volume (V) is in L ha-1 and concentration (C) is in kg ha-1. Area on the day of application (A) is provided by $AREA = MAX \times e^{\ln(\frac{MIN}{MAX})e^{-BT}}$

A Gompertz growth function using the parameters described in Table 2-1 was used to estimate fruit growth. Because it is an empirical approximation, the model does not use weather data to provide a more precise estimation of fruit area. An idealized growth curve for each scion is given by Equation 2-1 using the variables and parameters found in Table 2-2.

The idealized growth curve is calculated as follows:

$$AREA = MAX \times e^{\ln(\frac{MIN}{MAX})e^{-BT}} \tag{2-1}$$

where AREA is fruit surface area in mm^2, T is the sum of the current Julian day with the regression offset, MAX is the maximum measured AREA, MIN is an arbitrarily small value and B is the parameter for each scion type (Table 2-2).

Table 2-2. Parameters for calculation of fruit area extracted from the Copper Spray Scheduling Recommendation System (CuSSRS) source code.

Cultivar	Regression offset (Julian Day)	MAX (mm^2)	MIN (mm^2)	B (unitless)
Grapefruit	73	22,650	645 X 10^{-12}	0.0220
'Valencia'	69	14,949	645 X 10^{-12}	0.0222
Mandarin	77	14,263	645 X 10^{-12}	0.0198
'Navel'	64	19,856	645 X 10^{-12}	0.0214

Each day post application, the residue is reduced proportionally to the fruit surface area. The copper residue in μg cm^{-2} of a given day is calculated as follows:

$$RESIDUE = \frac{DEPO}{AREA} \tag{2-2}$$

Where DEPO is the initial residue from the most recent application and AREA is the current day's fruit surface area and calculated by Equation 2-1.

Rainfall events are responsible for rapid copper residue loss. The loss is proportional to the rainfall amount on a given day and the remaining residue. Table 2-3 shows how rainfall intensities have different effects on residue loss. The residue also slowly decreases over time because of the increase in the AREA value in Equation 2-2 while DEPO remains constant over time until there is a new application.

Table 2-3. Copper residue reduction formulas as a function of rainfall events separated into daily cumulative levels as extracted from the copper model source code.

Rainfall (mm)	Reduction[a]
> 0 and <= 127	$rLost = RESIDUE\ (\ 0.0189R\ )$
> 127 and <= 508	$rLost = RESIDUE\ (\ 0.18 + 0.04724R)$
> 508	$rLost = RESIDUE\ (\ 0.016535R\ )$

[a]Where R is daily rainfall in millimeters and RESIDUE is calculated by $RESIDUE = \frac{DEPO}{AREA}$.

Residue thresholds can be adjusted by the user in the CuSSRS model. For this study a residue threshold of 0.25 μg cm^{-2} was used as the 'danger' threshold. According to Albrigo et al. (2005), at the 0.25 μg cm^{-2} 'danger' threshold fruit still has complete protection. However an application is advised as soon as the 'danger' threshold is reached since a strong weathering event could leave the grove unprotected. When the residue falls under 0.1 μg cm^{-2} a grove is considered unprotected as the remaining residue is not sufficient to keep the fruit protected (Albrigo et al. 1997; 2005).

Web-based Interface Development on AgroClimate

The copper residue model was extracted from the CuSSRS Java source code and translated into the R language with the objective of facilitating the production of high quality graphs, its integration into the AgroClimate web server, and the execution of statistical analysis. The R statistical analysis software system (http://www.r-project.org) is a language and environment for statistical computing and graphics generation. It is an open-source implementation of the S language developed at Bell Laboratories by John Chambers and colleagues (R Development Core Team, 2011). R is multiplatform, which means that it can be run on all modern operating systems such as UNIX, Linux, Windows, and Macintosh. Being able to run under Linux is an important feature when integrating code with websites as the majority of web servers operate in Linux. R also provides a well-developed programming language and a self-contained environment to perform a wide range of statistical analyses. As a programming language, R is highly expansible allowing it to be easily adapted to new tasks that are not part of the built-in functionality (R Development Core Team, 2011).

Along with correcting the communication issues that prevented the CuSSRS to retrieve real-time weather data, the Citrus Copper Application Scheduler was intended to have a more functional and easier to understand interface, consequently broadening its use by citrus producers. With daily copper residue information, it is possible for growers to better time application decisions and reduce the number of unprotected periods. Lapses in residue protection can allow fruit infection to occur by plant pathogens decreasing their market value.

The tool was designed to be as simple as possible using only free and open source components following the AgroClimate website guidelines. The website runs in PHP, HTML (Hyper Text Markup Language), CSS (Cascading Style Sheets) and JavaScript using the jQuery framework (http://jquery.com/). Since it is available at a central server, it is possible to deliver updates and corrections with minimal delay.

The model and plots run in the R language. The inputs are stored in a MySQL (http://www.mysql.com/) database. To further assist decision-making, the tool is linked to the Citrus Pesticide Application Tool (http://fawn.ifas.ufl.edu/tools/pesticide/) available on FAWN that provides rainfall forecasts and application conditions for the next 45 hours.

Figure 2-2 shows a diagram of the different components of the copper residue simulation web tool. The simulation starts with the grower providing spray and grove information (Fig. 2-2A) on the PHP form. The user provided information is stored in the MySQL database (Fig. 2-2B) by the PHP algorithm, which also generates a system call to the R program containing the simulation (Fig. 2-2C). The simulation information is then retrieved by the R program from the database (Fig. 2-2D), which afterwards generates a HTTP call (Fig. 2-2E) to the FAWN web service retrieving (Fig. 2-2F) information from the weather station selected by the user. The copper residue simulation is then executed based on the information retrieved. The resulting graph is saved as an image in a specific folder on the server (Fig. 2-2H), the numeric results are saved back on the database (Fig. 2-2G). After the simulation is finished the PHP code which was halted by the system call continues to run (Fig. 2-2I), it reads the results as well as the location of the graph on the server (Fig. 2-2J-K) and presents the simulation information to the user (Fig. 2-2M).

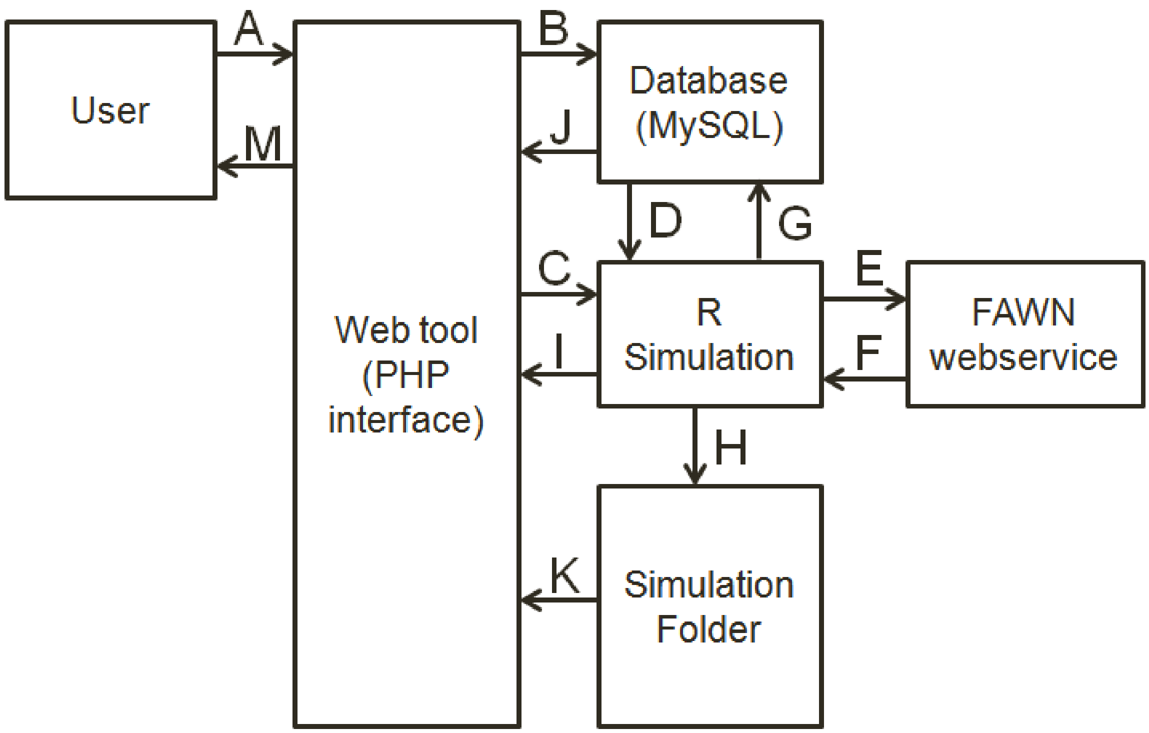

Figure 2-2. Components diagram of a copper residue simulation on the developed web tool.

All the experiments executed by the growers in the website stay anonymously logged in the database. Additionally, the Google Analytics™ tool was installed in the website. This tool allows tracking of the website traffic and users behavior. Using the logged information it was possible to create plots of the average bloom date, average concentration, and average volume inputted in the website. It was also used to generate a map of the number of user accesses to the website from Florida. This map was grouped by a political division called metropolitan area. These divisions are related to densely populated areas which share the same infrastructure, it might encompass several counties.

Analysis of the Copper Residue Using Historical Data

Having the Copper residue model translated to R enables the possibility of simulating scenarios using the historical meteorological data. These scenarios can produce valuable information regarding how different application approaches affected the copper residue in past years. More specifically, it is possible to count the number of days in which the grove was unprotected, the number of sprays necessary to achieve optimal protection, the effect of each model parameter in the results, and how different rainfall patterns affect the copper residue. It is also possible to test if the current spray recommendations provided adequate amounts of copper residue through the whole vulnerability period in different locations.

Meteorological Data

Daily precipitation data are a key input for the copper model as rainfall significantly reduces current residue levels on the fruit. In this study, two different meteorological data sources were used. The website tool uses observed data from FAWN weather stations located in citrus producing areas of the state. FAWN data were used for in-season simulation of copper residue levels and application scheduling. Historical analysis of copper application regimens needed a longer time series of daily weather data than the ones available from FAWN stations. For that reason, fifty-six years of historical daily weather data from the National Weather Service (NWS) Cooperative Observer Program (COOP) were used (http://www.nws.noaa.gov/om/coop). Five locations in the Florida counties of Highlands, Hendry, Lake, Indian River, and Polk were selected for the historical analysis aiming for a representative picture of the major citrus producing regions (Fig. 2-3). These counties account for 52% of Florida’s annual citrus production (FDACS 2012).

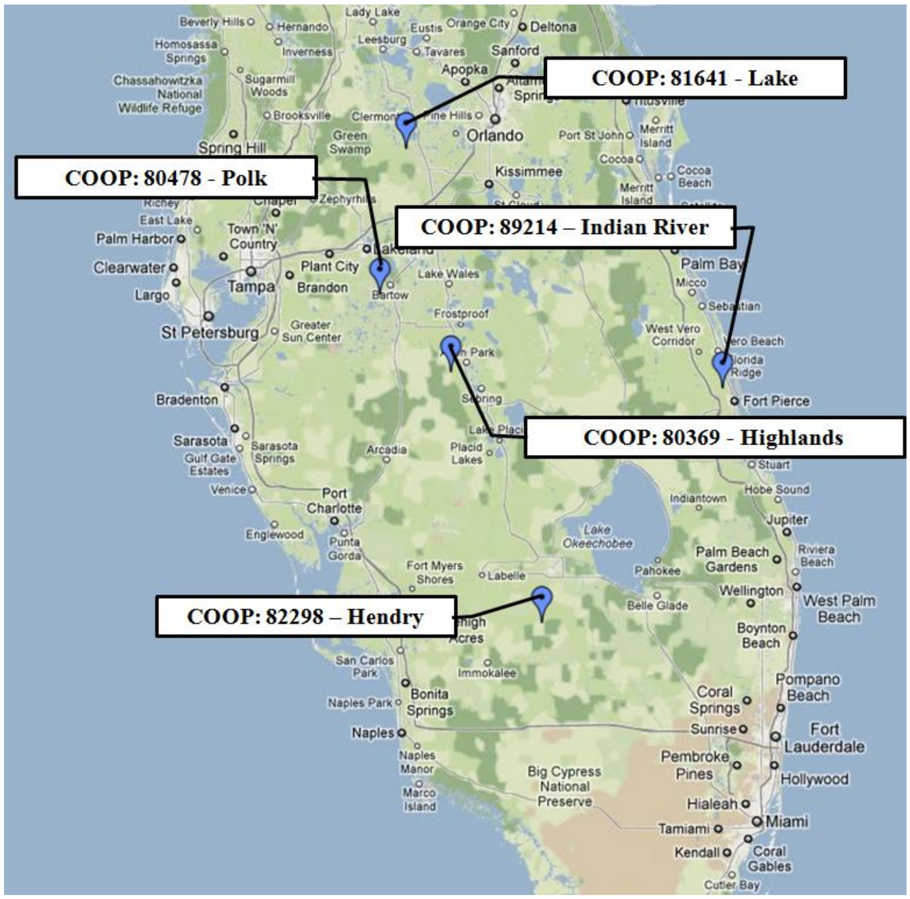

Figure 2-3. Selected National Weather Service (NWS) Cooperative Observer Program (COOP) stations for historical data analysis in Florida. Google and the Google logo are registered trademarks of Google Inc., used with permission.

Each year of observation in a location was classified according to its yearly accumulated rainfall as a wet, average, or dry year based on the first and third quartiles of the entire series. Every year with an accumulated rainfall greater than 1500 mm was classified as wet for that given location. Conversely, years with less than 1130 mm of accumulated rainfall were classified as dry, and all remaining years were considered to have had an average rainfall.

Analysis of Fruit Protection Based on the Traditional 21-Day Schedule

Several simulation experiments were conducted using the copper residue model and observed weather data to better understand the dynamics of copper residue decay and how different parameters affect copper residue levels. It was important to determine which combination of fruit position and scion defined the worst-case scenario. These parameters have a small but noticeable effect on the copper residue and knowing the worst-case scenario allowed the simulations to be restricted by assuming that other scenarios would have superior protection. The criteria used to determine the worst-case scenario was the number of unprotected days (residue < 0.1 µg cm^{-2}) for different scions and fruit positions using the traditional 21-day application schedule. This approach slightly reduced the precision of the analysis but greatly simplified the results by avoiding the need for different recommendation combinations for each fruit position and scion.

The simulation experiments produced in this study used the typical spray parameters for Florida: 0.84 kg ha^{-1} (0.75 lb ac^{-1}) metallic copper concentration and 1170 L ha^{-1} (125 gal ac^{-1}) volume (Dewdney et al., 2012a). The period in which the residue level was evaluated for unprotected days extended from the first spray 3 weeks post-bloom to the last day of July. The data for CuSSRS stopped in early July because the fruit are no longer susceptible to melanose (Albrigo et al. 2005), the main disease of concern prior to citrus canker and black spot.

For simulation standardization, three different peak bloom date scenarios were used to simulate early, average, and late bloom (Table 2-4).

Table 2-4. Traditional 21-day spray schedule with early, average, and late peak bloom scenarios.

Event	Early bloom	Average bloom	Late bloom[a]
Bloom date	10-Mar.	20-Mar.	30-Mar.
1st spray	31-Mar.	10-Apr.	20-Apr.
1st scheduled spray	21-Apr.	1-May	11-May
2nd scheduled spray	12-May	22-May	1-June
3rd scheduled spray	2-June	12-June	22-June
4th scheduled spray	23-June	3-July	13-July
5th scheduled spray	14-July	24-July	N/A
End of vulnerability period	31-July	31-July	31-July

[a] N/A not applicable

Analysis of Fruit Protection Based on the Web Tool Recommendations

An R program was developed to compare the amount of copper used by the traditional 21-day copper schedule and the hypothetical case in which producers are able to spray whenever necessary (copper residue under 0.25 μg cm^{-2}) according to the citrus copper application scheduler recommendations. For this comparison we used an average bloom period, copper concentration of 0.84 kg ha^{-1}, spray volume of 1170 L ha^{-1}, the mandarin scion, and 56 years of rainfall data for all the studied locations. The objective of the comparison was to measure how many copper applications would be necessary per year to achieve no unprotected days assuming that the web-tool recommendations were followed to the letter. Additionally, the difference in residue levels between dry, average and wet years were calculated.

Sensitivity Analysis of The Model to Application Parameters

Aside from application dates, the spray concentration and volume are the only parameters that can be easily changed by the producer to achieve better protection. Although recommendations for these parameters already exist (Dewdney et al., 2012a), it was important to understand the model sensitivity to them. The model was run by varying both metallic copper concentration and diluent volume one at a time, small increments, while all other parameters were kept the same. This approach is known as 'vary one parameter at a time' sensitivity analysis. Many other more complex sensitivity analysis approaches have been proposed. These more complex approaches better cover the search space as in the Morris method (Morris et al., 1991) or use variance decomposition as in the FAST method (Schaibly et al., 1973) but these are better suited for large models with unpredictable interactions between the inputs.

For the 'vary one parameter at a time' approach, it is necessary to define the range in which the parameters can vary. The spray volume range was varied from 467 to 4676 L ha^{-1} by increments of 9.3 L ha^{-1} and the concentration range was varied from 0.56 to 4.48 kg ha^{-1} by increments of 0.056 kg ha^{-1}. These are the maximum and minimum values that were used by producers on the web-tool. It was also necessary to define the default values for the other model parameters while only one is varied in each simulation. The typical 21-day spray schedule, average bloom date, inside canopy fruit position, copper concentration of 0.84 kg ha^{-1}, spray volume of 1170 L ha^{-1}, the mandarin scion, and 56 years of rainfall data were used for all the studied locations.

This sensitivity analysis approach also required relevant output to be selected. The sum of the number of unprotected days from the first spray to the end of July across all years of weather data and locations was selected.

Copper Application Schedule Optimization

Disease control is not always satisfactory with the traditional 21-day schedule and many Florida citrus farms encompass thousands of hectares or are scattered over wide areas. In these cases, it is not always possible to quickly move equipment according to output from a daily model and a compromise was sought to improve the copper coverage over the traditional schedule for these operations on a set schedule. It was hypothesized that historical weather data along with the fruit growth and copper residue decay estimates from the CuSSRS could be used to develop a dynamic copper application schedule with fewer coverage gaps to improve disease management in the spring and early summer.

Considering that each location had slightly different historical rainfall pattern, a more optimized schedule for each independent region would exist. This region specific optimization would produce better results than one optimized for all the regions. However, there would be a total of 15 optimized schedules, one for each region and bloom date. It was decided not to publish these results as they were overly complicated for the producers and the additional protection benefit small.

Optimization of Fruit Protection Using a Varying Interval Schedule

Based on initial observations from the model output, it was determined that the driving factors behind copper residue loss, fruit growth and rainfall, vary throughout the growing season. It was then possible to develop a fixed schedule that adjusted the interval between sprays during the growing season to account for different growing conditions and weather patterns that could result in more uniform protection.

To further study this hypothesis, an R schedule optimization algorithm was developed with the objective of generating and testing different scheduling strategies aimed at the best protection with model outputs and historical weather data. The generated schedules were ranked by the resulting fruit protection. More specifically the fruit protection is given by the sum of unprotected days over every year from 1956 to 2012 across the 5 studied locations. The simulations used the worst-case scenario for fruit position and scion, typical spray parameters, and the first spray started 21 days after bloom (Fig. 2-4). The number of unprotected days was calculated also for the traditional 21-day schedule with the same parameters to serve as a baseline scenario.

The number of schedule simulations that could be tested was limited by the substantial computational processing required for this task. The ideal scenario would be to vary each date for at least +6 to -6 days, but this approach for a 5-spray date season would create 371,293 different schedules. Considering it would be necessary to run all these schedules for each of the 56 years for each of the 5 locations, it would create an impractical total of over 100 million simulations. A more manageable and sophisticated approach was to vary each schedule for +2 to -2 days requiring only 3,125 whole year simulations. Then use this local minima result and re-run it again starting out from the optimized schedule. This process was repeated each time using the best result from the previous schedules until the resulting optimum schedule was the same as the starting schedule provided to the algorithm. It is very likely that the result of this approach is also the global minima because the best schedules usually are similar. However, it can only be guaranteed to be the local minima in the last run range.

For example, the first experiment for the early bloom date tested schedules with spray intervals ranging from (19, 19, 19, 19, 19) to (23, 23, 23, 23, 23). These extreme schedules were obviously not suitable as the first one would produce a period of low residue in July and the last one simply has too many days between applications leaving the grove vulnerable. Among all the possibilities there is likely a more efficient schedule than the 21-day fixed schedule.

There was little difference between the residual copper losses of the different scion types which supported the contention that it was acceptable to create the optimized schedules based on the worst-case scenario. With the worst-case scenario as our test subject, the residue decay predictions for the other scion types are likely to be conservative. This means that if there is an error in the prediction, it is likely to encourage an application before needed but not allow a lapse in coverage.

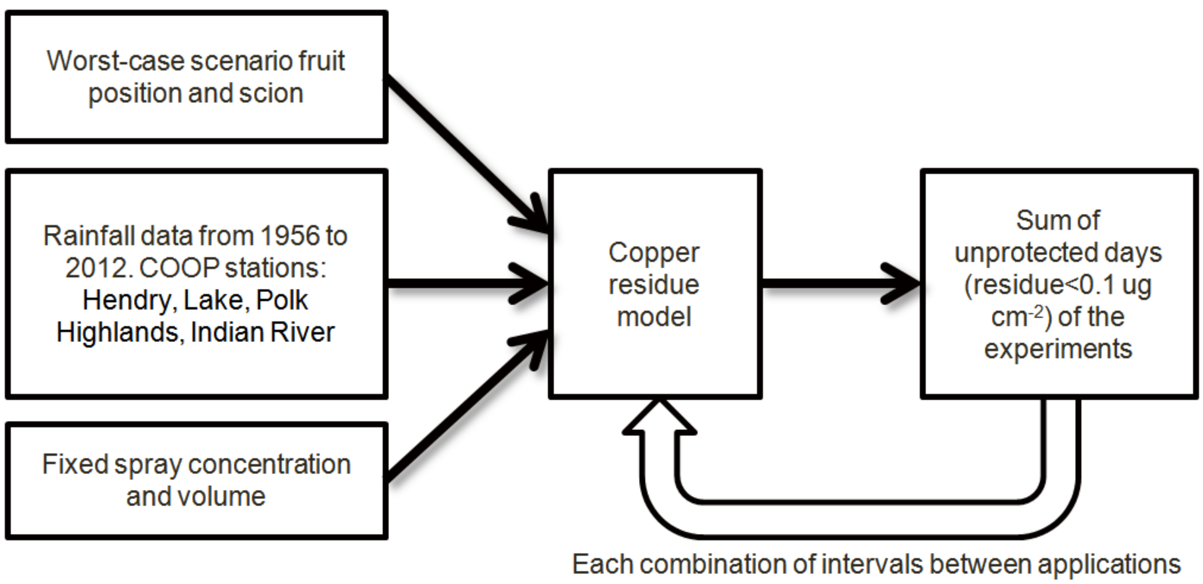

Figure 2-4. Steps of the program created to analyze combinations of different intervals between each copper application.

The proposed approach was not supposed to increase amount of copper applied compared to the amount that would otherwise be applied with the 21-day schedule. For this reason in the case of late bloom, only 4 copper applications were simulated, 5 applications would have extended the protection past the vulnerable period (Table 2-4).

Optimization of Fruit Protection Using a Varying Concentration Schedule

It is a common practice of Florida growers to combine several products in the spraying equipment tank in order to minimize costs. These products also have set schedules, which might complicate the usage of the proposed varying interval schedule.

For these cases, a dynamic schedule was proposed, which varies the concentration of each application and still has the fixed 21-day schedule. This approach is less effective because the residue lost per day is proportional to the current residue on the fruit. Consequently greater concentrations also produce greater loss of residue reducing the overall possible gain in protection.

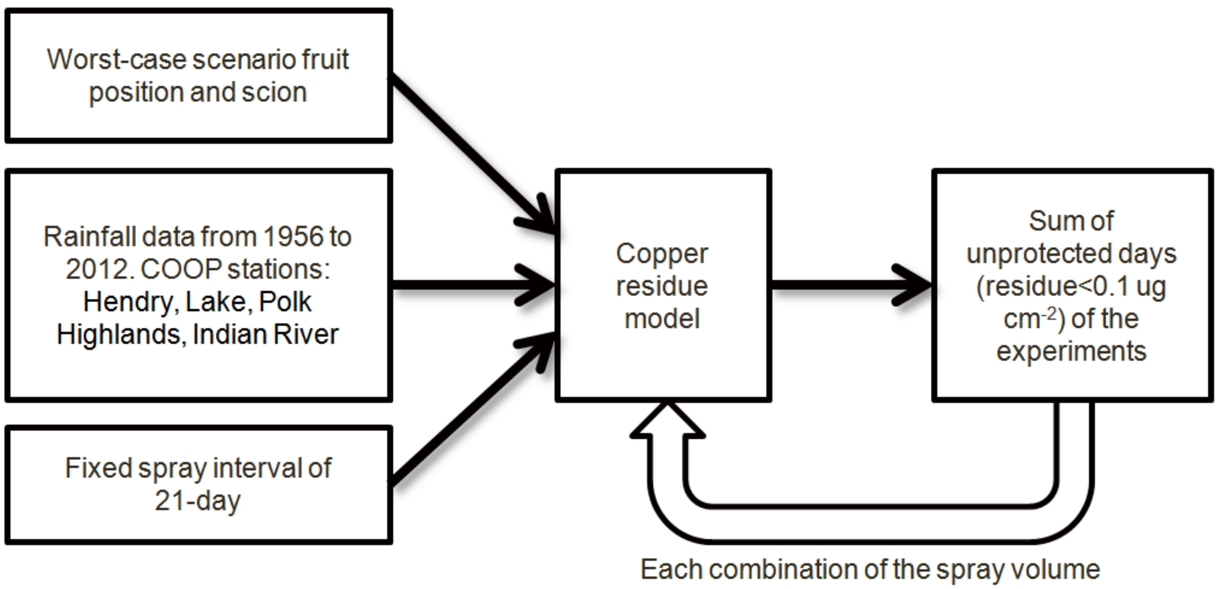

Figure 2-5. Steps of the program created to analyze combinations of different concentrations on each copper application.

For the varying concentration schedule it was necessary to also vary the concentration of the first application, which was fixed in the varying interval schedule. This approach increased the number of possible schedules by 5 times, however the number of valid proposed schedules was greatly reduced by the fact that this approach was not supposed to increase the amount of copper applied, consequently limiting the valid schedules to only those which fit this criteria. The concentrations were varied by

±0.122 kg ha^{-1} (0.10 lb ac^{-1}) with a range of ±0.224 kg ha^{-1} (0.20 lb ac^{-1}) in each run of the optimization algorithm.

Summary

In this chapter, it was presented a detailed description of the copper model which is used in this study including equations and overall structure. It was also described the methodologies and parameters used in the simulations for accessing copper protection performance in past scenarios. Additionally, the approach for optimizing both interval of application and copper concentration in each application optimizations was described. In chapter 3, it will be presented optimization results, analysis of the current recommendations for Florida, and the developed and implemented web-tool for simulating copper residue levels.

CHAPTER 3
RESULTS AND DISCUSSION

Web-tool

The web-based application developed for this study works as a practical interface for the producer with the citrus copper application scheduler. With the daily residue information, it is possible for producers to make accurate and timely decisions regarding copper applications. To operate the system, the user inputs the spray concentration and volume, scion, bloom date and weather data source (Fig. 3-1). This source can be either the FAWN weather station closest to the grove or a comma separated value (CSV) file containing the user's rain measurements. The 'Simulate copper residue' button creates a graph that shows the daily copper residue from 3 days before first spray until a week after the current day. The blue bars indicate rainfall events and the red/yellow areas are the danger and warning thresholds respectively. When the residue reaches the warning level, the grower is advised to plan for an application. When the residue reaches the danger zone, the grower is advised to make an application as soon as possible. Additional information about the system's operation can be found in (Dewdney et al. 2012a).

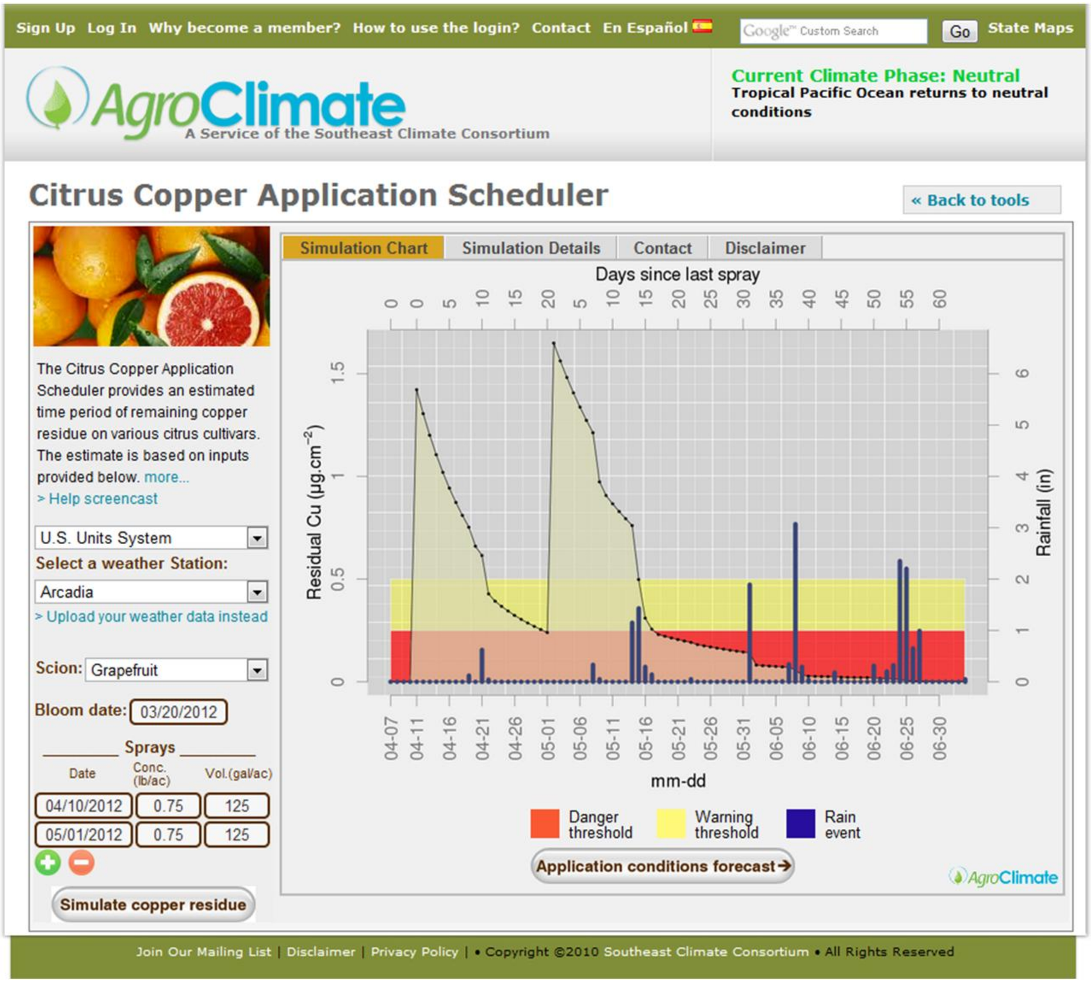

Figure 3-1. The citrus copper application scheduler on the AgroClimate website (July, 2012).

The user also can see the model results in table format or download them as a CSV file. A detailed screencast on how to use the website is provided in the link 'Help screencast'. Clicking on the corresponding data fields allows the user to change the default quantity of metallic copper per area and spray volume. To calculate the kilograms of metallic copper used, it is necessary to multiply the percent metallic copper in a product (found on the label) by kg ha^{-1} used. The fruit position is not requested because it would not make sense to ask that question to a producer; instead the worst-case scenario is always assumed (fruit inside the canopy).

Model Evaluation

Simulation results of the traditional 21-day schedule (Table 3-1) indicate that of all scion combinations and fruit positions, the fruit inside the canopy of a mandarin type scion were the least protected with an average of 3.12 unprotected, under 0.1 µg of copper cm^{-2} , days per year. This combination of parameters was then considered to be the worst-case scenario and used in all other simulations in this study.

Table 3-1. Number of unprotected days as determined by the copper residue simulation using 56 years of weather data for each region with a 21-day application schedule and average peak bloom date (March 20).

Florida County	Grapefruit			Valencia			Mandarin		
	Tot.[a]	Max	Avg.[a]	Tot.	Max	Avg.	Tot.	Max	Avg.
				Fruit inside the canopy					
Hendry	257	26	4.59	271	27	4.84	282	27	5.04
Highlands	153	21	2.73	167	21	2.98	171	21	3.05
Indian River	102	13	1.82	116	14	2.07	119	14	2.12
Lake	114	14	2.04	125	15	2.23	138	15	2.46
Polk	153	11	2.73	167	11	2.98	174	11	3.11
Average	156	-	2.78	170	-	3.02	177	-	3.16
				Fruit on the canopy surface					
Hendry	150	23	2.68	160	23	2.86	166	23	2.96
Highlands	74	12	1.32	78	12	1.39	83	15	1.48
Indian River	49	11	0.88	52	11	0.93	55	11	0.98
Lake	41	10	0.73	49	10	0.88	49	10	0.88
Polk	67	8	1.20	72	8	1.29	71	8	1.27
Average	76	-	1.36	84	-	1.47	85	-	1.51

[a] Tot. – total
Avg. –average per year

Table 3-2 shows the simulated maximum and average unprotected days using the worst-case scenario parameters for each yearly-accumulated rainfall classification. The minimum is not displayed because it was 0 for all the proposed scenarios. There is a large difference in the number of unprotected days in wet years compared to dry years, with more unprotected days occurring in wet years.

Table 3-2. Number of unprotected days as determined by the copper residue simulation using 56 years of weather data for each region with a 21-day application schedule and average peak bloom date.

Florida County	Dry[a]		Average[a]		Wet[a]	
	Max	Avg./year	Max	Avg./year	Max	Avg./year
Hendry	4	1.07	16	5.58	27	7.18
Highlands	7	0.71	13	3.22	21	4.62
Indian River	6	0.81	13	2.18	14	3.46
Lake	8	1.15	11	2.21	15	4.55
Polk	7	1.29	10	2.68	11	5.40
Average	-	1.00	-	3.17	-	5.04

[a] Classification based on the first and third quartiles of the yearly accumulated rainfall. Years with accumulated rainfall greater than 1500 mm were classified as wet. Years with accumulated rainfall less than 1130 mm were classified as dry and all remaining years were considered to have had an average rainfall.

Figure 3-2 shows a residue simulation of a typical wet year, 2008, for Hendry County showing the difference in residue decay between grapefruit and mandarin. In this scenario, the grove would have been unprotected from June 26th to July 2nd and from July 15th to the end of the season with the traditional 21-day application schedule. This was a typical case in which a varied application schedule would have provided much more efficient protection with the same amount of copper by delaying the first 3 applications. There were little differences between the residual copper decay of the different scions.

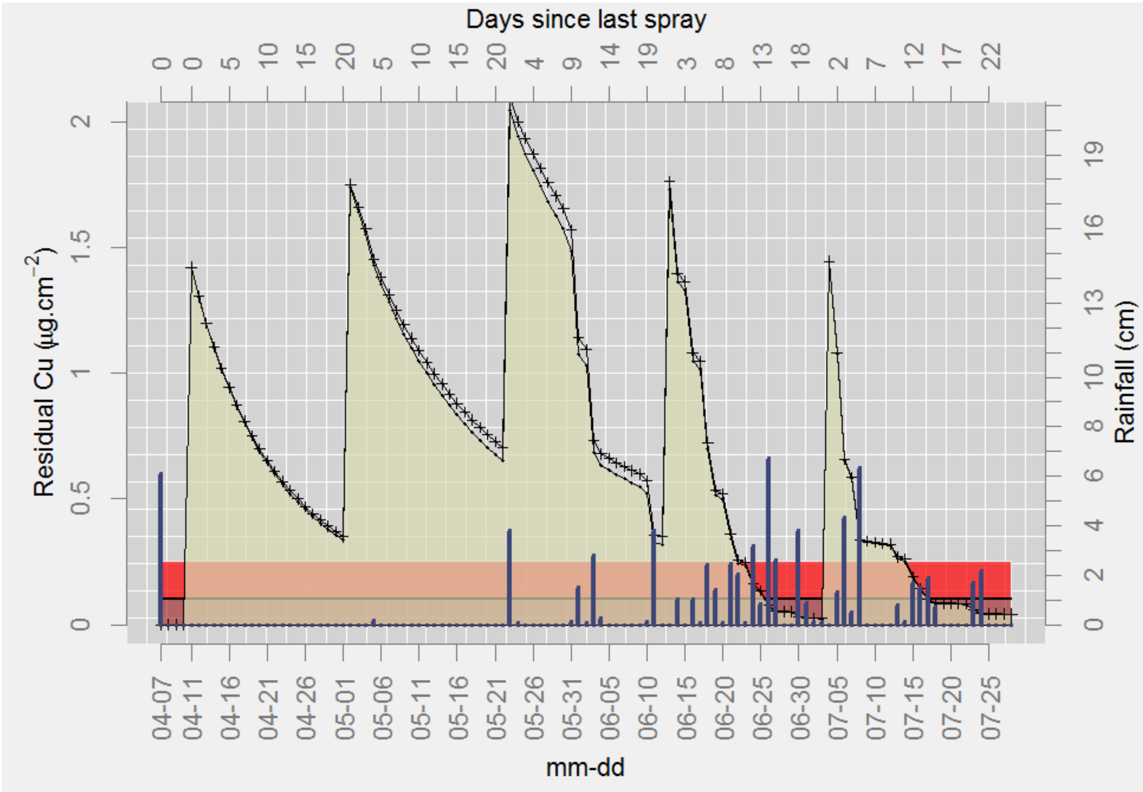

Figure 3-2. Copper residue simulation for Hendry County in 2008 using the 21-day schedule and typical spray parameters (0.84 kg ha^{-1} metallic copper concentration and 1170 L ha^{-1} volume). The crosses are residue on grapefruit and dots are residue on mandarins. The red threshold is 0.25 µg cm^{-2} of copper and the black line is 0.1 µg cm^{-2}. The blue bars are daily total rainfall.

In contrast to wet years, a substantial amount of copper is often wasted in dry years. For example, Figure 3-3 shows the copper residue continuously accumulated from April to July, 1998. Yet, in July even a small amount of rain washed off most of the copper residue because the residue loss is proportional to the residue present (Table 2-1). This is in agreement with the current theory that there is no reason to apply large amounts of copper in fewer sprays (Timmer et al., 1998). Based on the model, only 3 timed applications were able to keep sufficient copper residue levels thus avoiding 2 unnecessary copper applications (Figure 3-3).

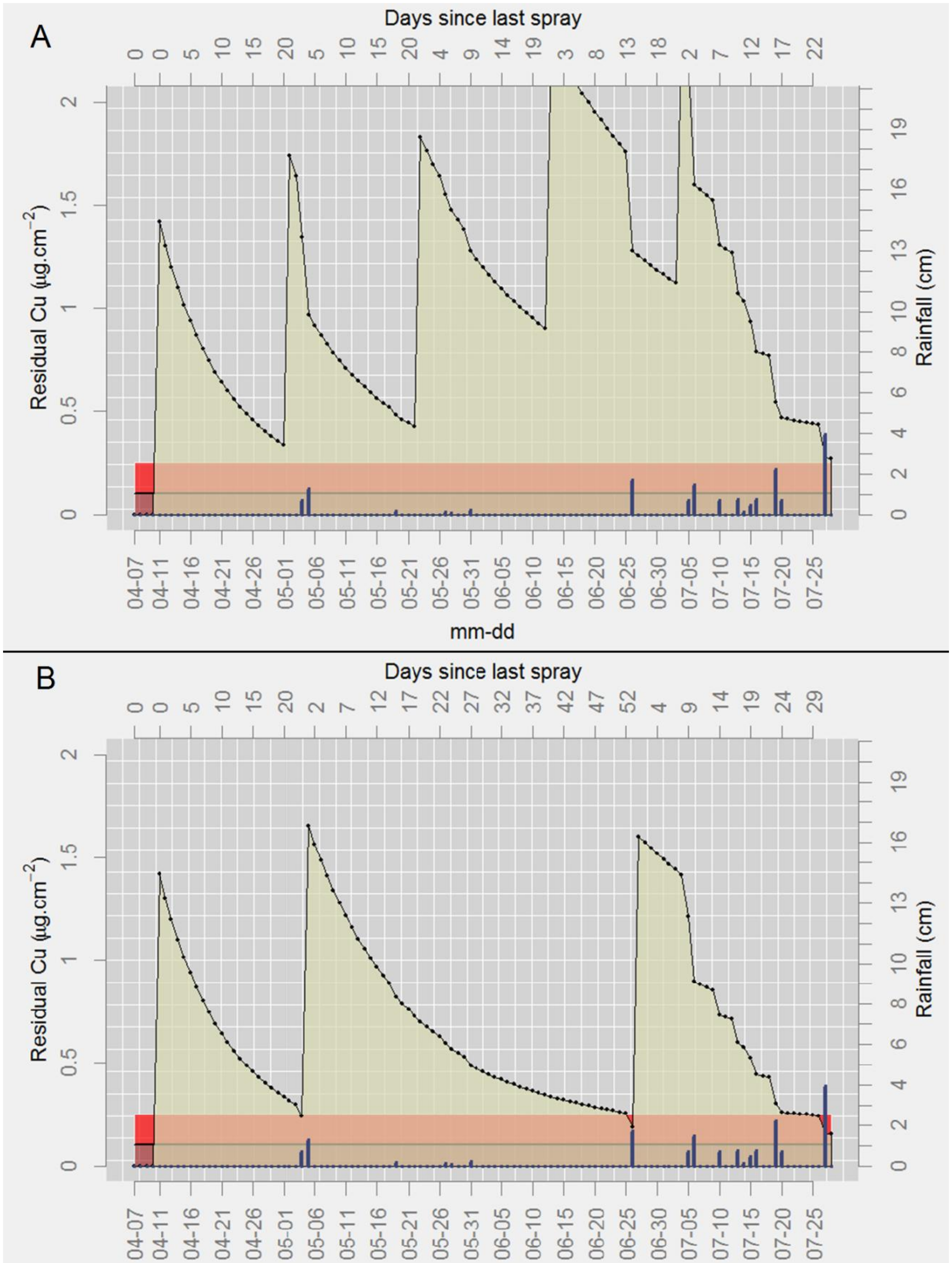

Figure 3-3. Comparison between the 21-day spray schedule (A) and the ‘spray when danger threshold reached (in red)’ method (B). These simulations were run using 1998 Lake County weather data for mandarin types and typical spray parameters (0.84 kg ha^{-1} metallic copper concentration and 1170 L ha^{-1} volume) and the traditional 21-day schedule. The red threshold is 0.25 µg cm^{-2} of copper and the black line is 0.1 µg cm^{-2}.

The citrus copper application scheduler can be used to estimate summer copper residue decay but it may not be as accurate as for early season estimates. The causes of these potential inaccuracies include the fruit growth curves, which estimate growth between petal fall and early July, when growth is faster than in the summer. After this period, our preliminary data showed a slower fruit expansion over the summer and fall. In addition, rainfall becomes more scattered with thunderstorms and potentially more intense during the summer compared to spring and early summer. It is not known how the slowing of fruit growth along with the seasonal change in rainfall patterns can affect copper residue levels. Summer copper residue predictions will eventually be improved with data generated by on-going experiments.

Sensitivity Analysis

With the 'vary one at a time' sensitivity analysis of the spray volume (Fig. 3-4), it was possible to demonstrate that different volumes change the number of unprotected days. The recommended volume of 1170 L ha^{-1} volume is located exactly on the optimal protection point.

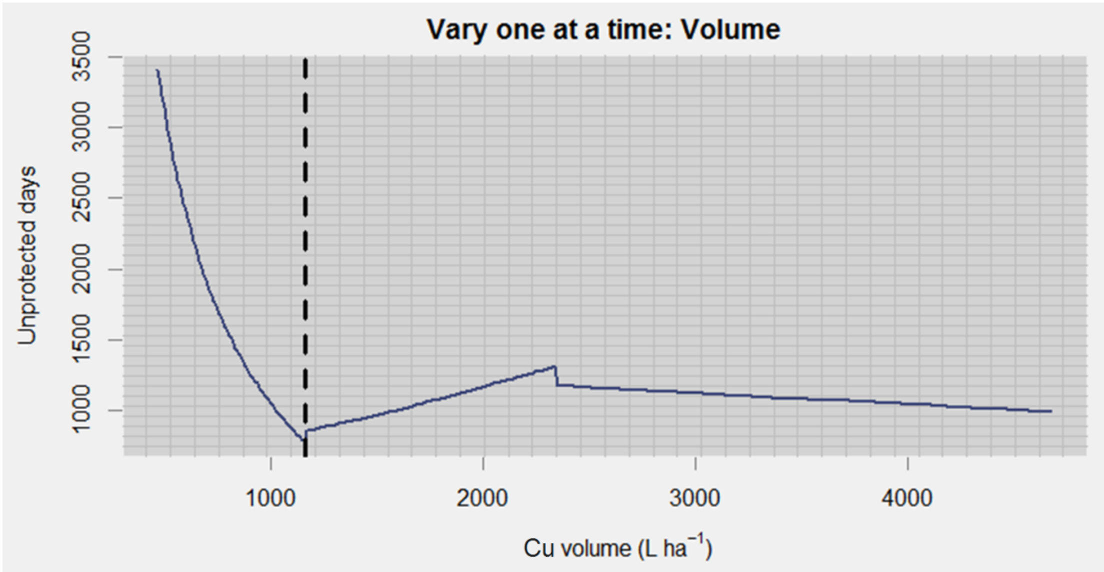

Figure 3-4. Number of unprotected days summed across 56 years of every weather station. Each data point shows the simulated results varying only the spray volume from 467 to 4676 L ha^{-1} by increments of 9.3 L ha^{-1}. All the other inputs for the model were kept fixed according to the defined worst case scenario. The dashed line shows the current recommendation of 1170 L ha^{-1} result.

Figure 3-5 shows the ‘vary one at time’ concentration sensitivity analysis. This parameter had a logarithmic impact on the number of unprotected days. The recommended concentration of 0.84 kg ha^{-1} is a well-balanced value between a reasonable amount of protection and an economical use of copper. It was also shown that concentrations greater than 1.5 kg ha^{-1} should be avoided as they provide little increase in protection while increasing the chance of fruit blemishes caused by copper phytotoxicity.

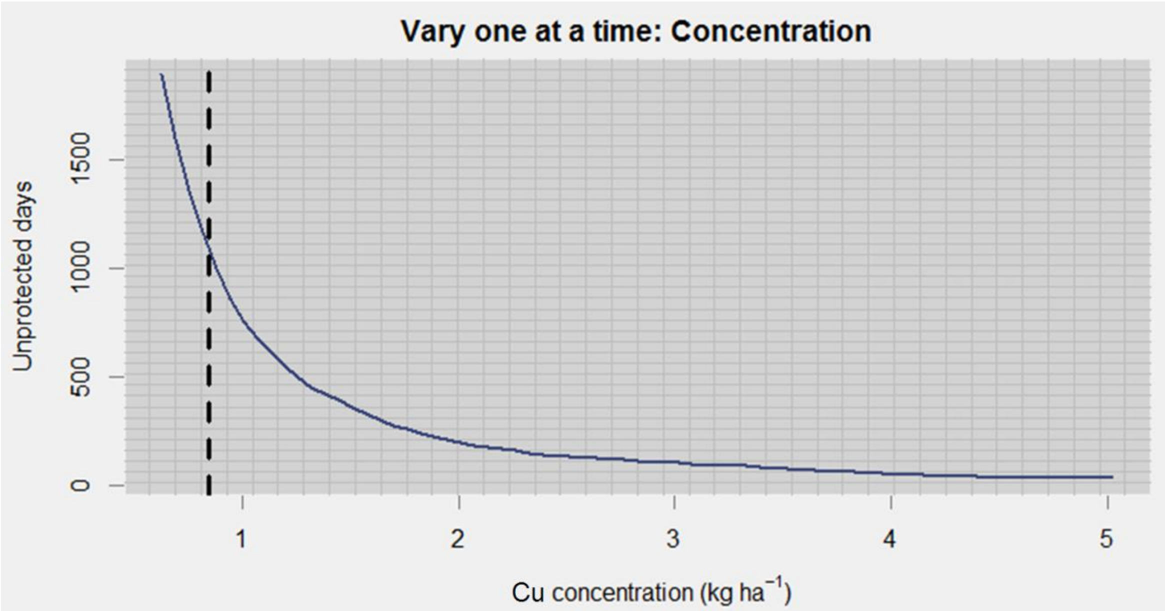

Figure 3-5. Number of unprotected days summed across 56 years of every weather station. Each data point shows the simulated results varying only the spray concentration from 0.56 to 4.48 kg ha^{-1} by increments of 0.056 kg ha^{-1}. All the other inputs for the model were kept fixed according to the defined worst case scenario. The dashed line shows the current recommendation of 0.84 kg ha^{-1} result.

System Evaluation

The citrus copper application scheduler allows citrus producers to achieve greater precision in the grove’s copper residue. For instance, in some exceptionally dry years, even with the worst-case scenario of mandarin fruit inside the canopy, only 3 standard copper applications were able to keep the residue levels over the danger threshold for the entire season (Fig. 3-3) in the simulated scenarios. On the other hand, Figure 3-6 shows an extreme case of a year with intense rainfalls where seven applications were necessary to hold the residue always above the danger threshold. With the traditional 21-day schedule, there would have been several critical gaps in copper coverage.

The same approach of applying copper when the danger threshold is reached was then simulated for all 56 years of weather data and all stations. These simulations showed that across all locations in average years it would be necessary to use 6.2 standard copper sprays to keep the residue above the danger zone with the average bloom scenario. Also, the average period between needed applications was 20.6 days; this number suggests the current recommended 21-day schedule is a reasonable average. However, many years are not 'average' and there are gaps in coverage or excess applications for very wet or dry years, respectively (Table 3-3).

Table 3-3. Statistics of the spray applications using the 'spray on danger threshold reached' method for all 56 years. Typical spray parameters and average bloom period were used. The worst-case scenario, mandarin fruit inside the canopy, was used as plant parameters.

Florida County	Average number of applications (wet years)	Average number of applications (average years)	Average number of applications (dry years)	Average number of days between applications (all years)	Average yearly rainfall (mm) (all years)[a]
Hendry	6.4	6.2	5.7	19.2	587
Highlands	6.4	5.9	5.4	20.4	537
Indian River	5.8	5.5	5.0	21.9	444
Lake	6.4	5.9	5.0	21.0	512
Polk	6.3	5.8	5.4	20.5	536
All Counties Averaged	6.2	5.8	5.3	20.6	523

[a] In the considered period, from first spray to 31 July.

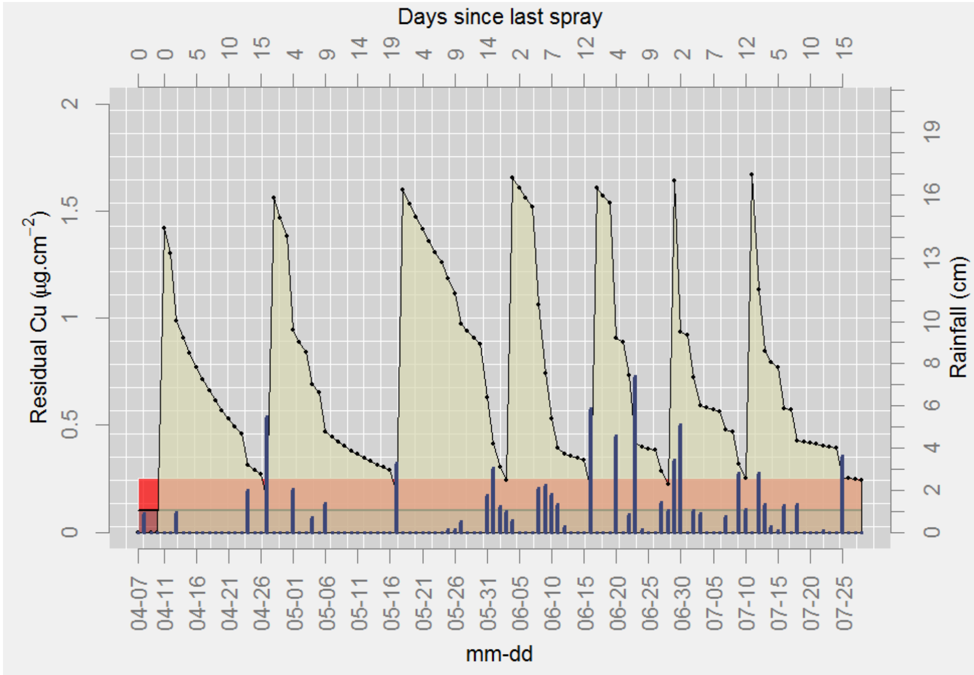

Figure 3-6. Copper residue simulation using worst-case scenario plant parameters, mandarin fruit inside the canopy, 0.84 kg ha^{-1} metallic copper concentration, 1170 L ha^{-1} volume, and Polk County weather data of 2005. The spray schedule used was the 'spray on danger threshold reached'. The red danger threshold is 0.25 µg cm^{-2} of copper and the black line is 0.1 µg cm^{-2}.

Web-tool Usage Statistics

Figure 3-7 shows the number of unique visitors from Florida to the created web-tool. This figure is restricted to only visits incoming from Florida; other areas with significant number of visits include California, Brazil and China. The central Florida region had a greater number of visitors, this is an expected result as this area has the most Citrus production (Figure 1-1). However, the large number of visitors from the Gainesville area is explained by tests by the staff of University of Florida and is not representative of the Citrus producers.

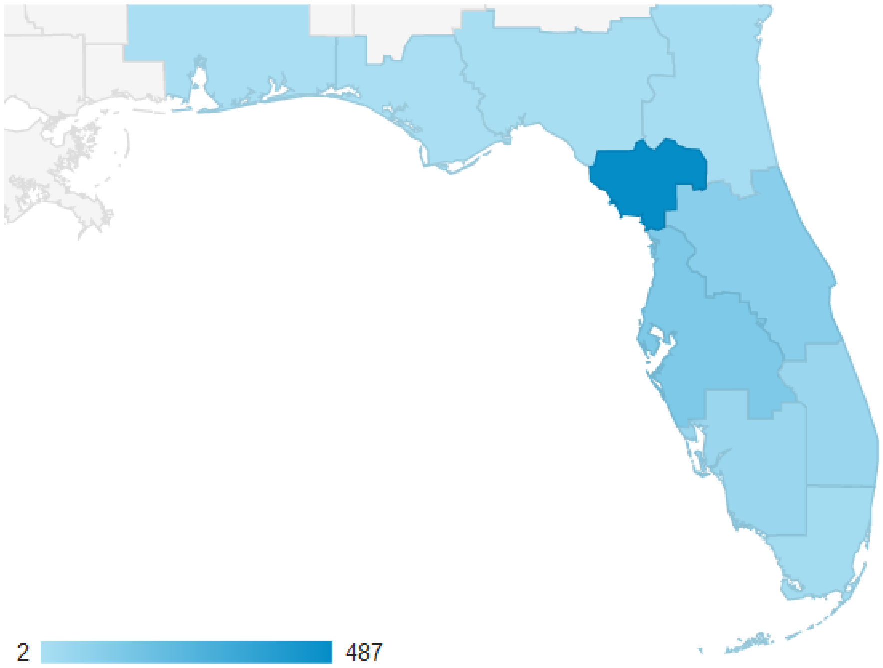

Figure 3-7. Map of Florida showing number of unique visitors of the Copper web-tool produced using Google Analytics™. The visitors are grouped by metropolitan areas. Google and the Google logo are registered trademarks of Google Inc., used with permission.

Figure 3-8 shows a Gaussian kernel density estimate of the bloom dates recorded by the web-tool. A peak of bloom dates around mid March can be observed, this peak is in agreement with proposed bloom dates of the executed experiments (Table 2-4). The peak in the beginning of the year however is explained by the fact that the website suggests a valid date up to 21 days before the current date as default value for bloom date, consequently most of the users visiting the website in January will have the date automatically set to January 1st increasing the odds of these dates.

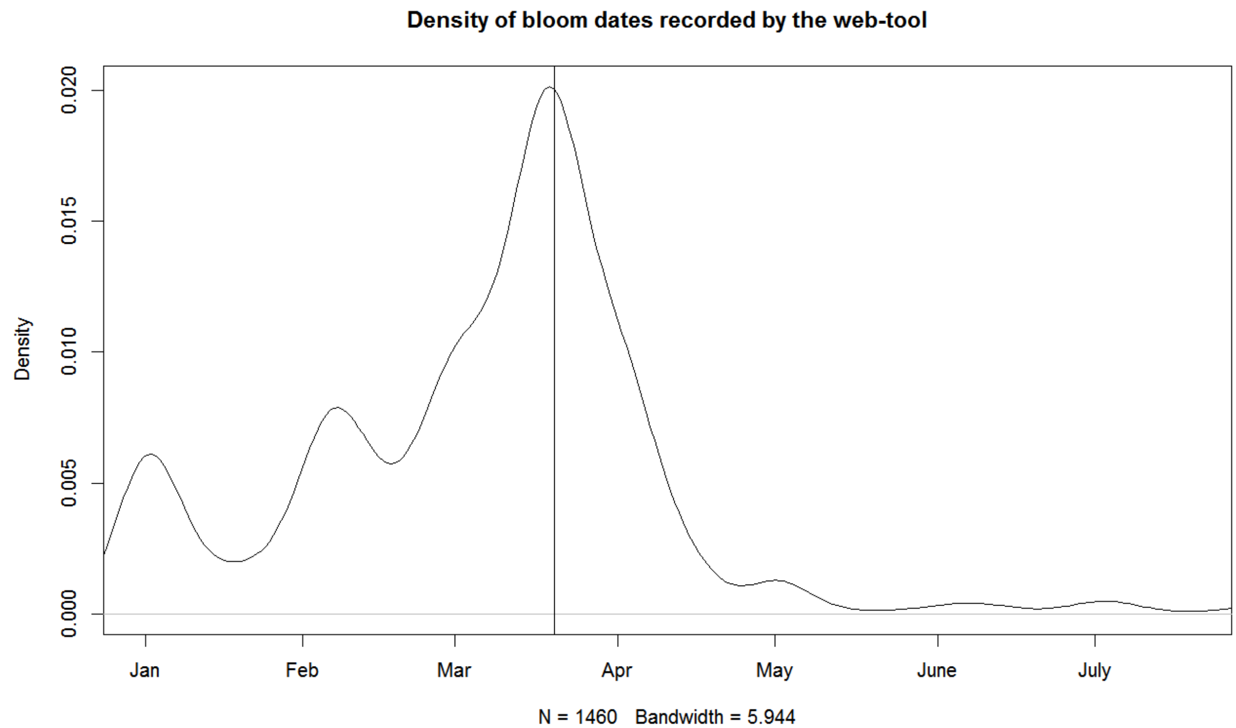

Figure 3-8. Plot of a Gaussian kernel density estimate of the 1460 bloom dates recorded by the web-tool. The vertical line marks March 20th which is the suggested average bloom date.

Figure 3-9 shows a Gaussian kernel density estimate of 3259 spray volumes recorded by the web-tool. The peak at 125 gal ac^{-1} shows that most of producers do not modify the suggested default value, but there are also noticeable peaks at 200 and 250 gal ac^{-1}. This result suggests that some producers use more diluted spray applications.

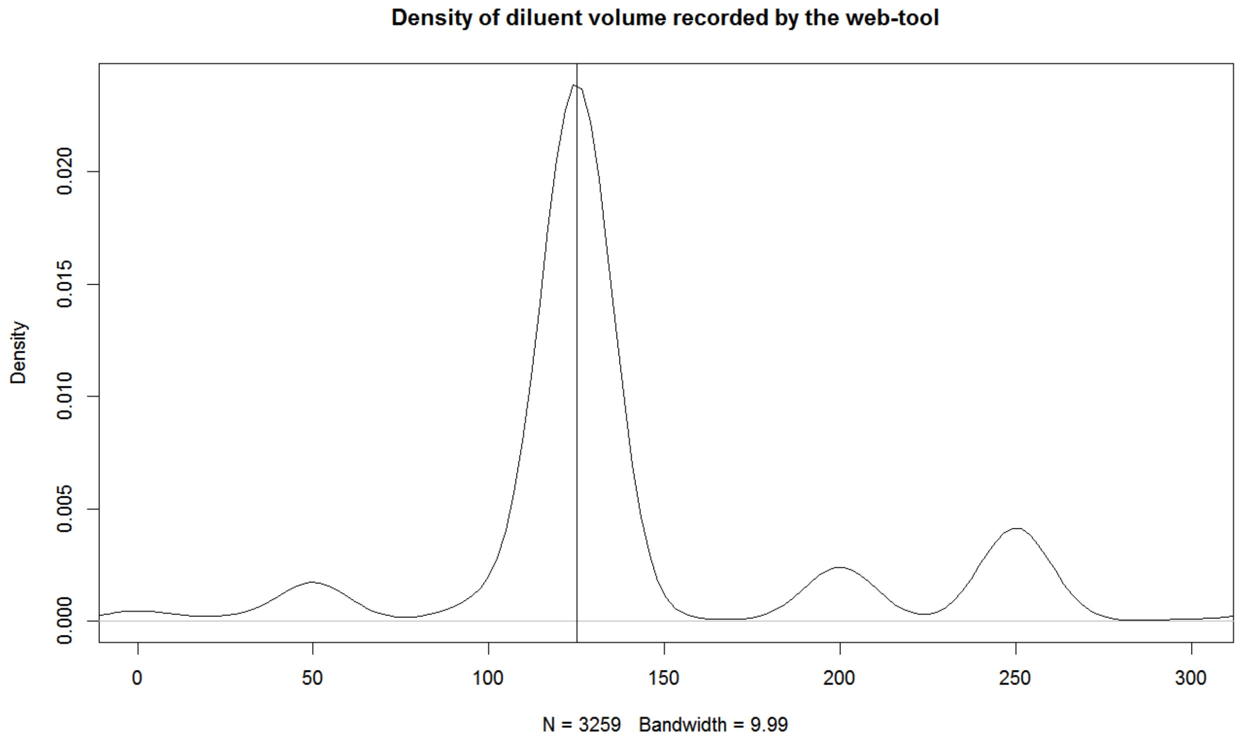

Figure 3-9. Plot of a Gaussian kernel density estimate of 3259 spray volumes recorded by the web-tool. The vertical line marks 1170 L ha^{-1} (125 gal ac^{-1}) concentration which is the current recommendation.

Figure 3-10 shows a Gaussian kernel density estimate of 3259 spray concentrations recorded by the web-tool. The peak at 0.75 lb ac^{-1} shows that most of producers do not modify the suggested default value, however there are several high concentration peaks at 1.5, 2.0 and 3.0 lb ac^{-1}. These results suggest that many producers still use high concentration applications, which were shown to provide little increase in protection.

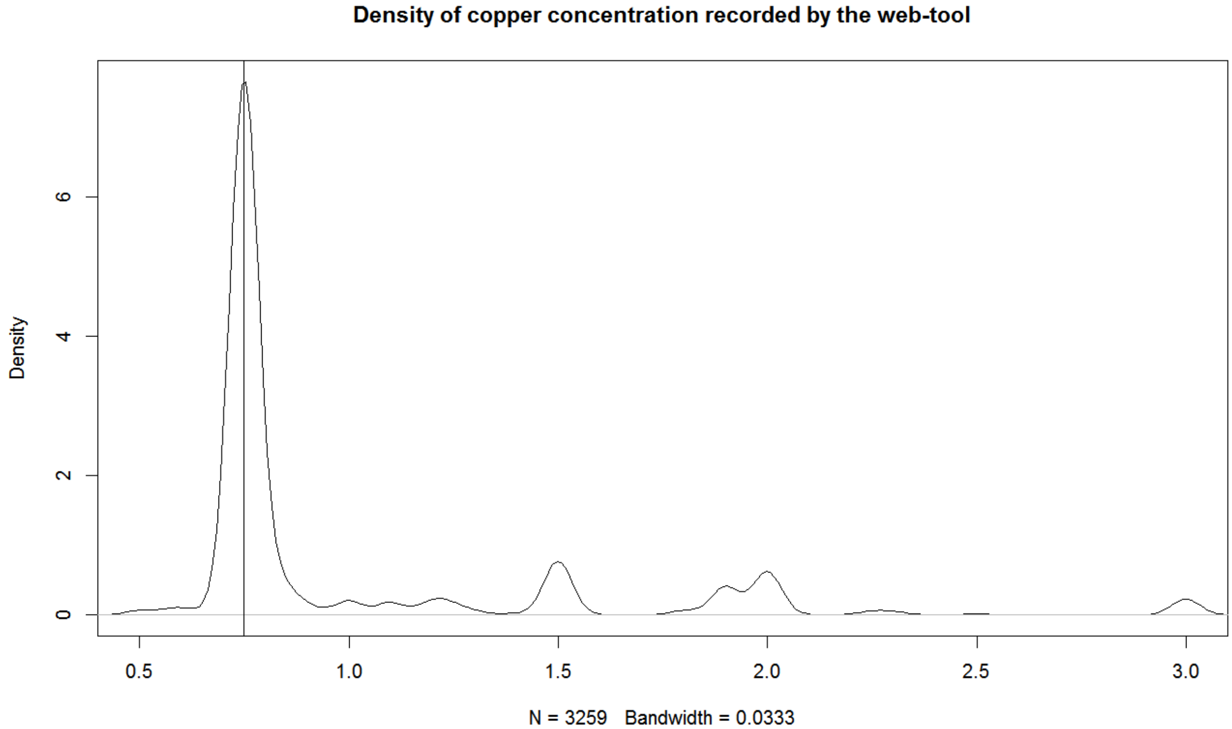

Figure 3-10. Plot of a Gaussian kernel density estimate of 3259 spray concentrations recorded by the web-tool. The vertical line marks 0.84 kg ha^{-1} (0.75 lb ac^{-1}) concentration which is the current recommendation.

It is important to realize that web sites statistics have strong biases towards default values and towards the region in which the website was produced. This subsection would have more realistic information if it was possible to exclude all the traffic incoming from University of Florida and if every field on the web-tool had no default values. Yet default values are crucial for the web-tool usability and help the producers to be aware of the recommended parameters.

Dynamic Optimized Schedules

For each peak bloom date scenario, the R schedule interval optimization algorithm was run until the dates converged to a point at which no better schedule was found. On average, 3 executions of the optimizing algorithm were needed. Table 3-4 shows the result of each algorithm execution. It is important to remember that each peak bloom date scenario has its own schedule. Consequently for scions with large differences in the peak bloom date or different vulnerability period, these schedules should be modified to reflect the new conditions. The reduction column of Table 3-4 refers to the reduction in the number of unprotected days when compared to the usual 21-day interval schedule. The average number of unprotected days per year/station using the 21-day interval schedule for early, average and late bloom were respectively 2.38, 3.10 and 3.78.

Table 3.4 Schedules resulting from the interval optimization algorithm. These results consider all years of available weather data and all locations average, the worst-case scenario as plant parameters and typical spray volume and concentration.

Peak Bloom	Interval to spray[b]					Average of unprotected days per year/station	Reduction %[c]
	1st	2nd	3rd	4th	5th		
Early	20	24	21	19	19	1.9	18.9
Average	19	24	16	17	17	1.5	50.9
Late	22	22	20	19	N/A[a]	3.3	11.7

[a] Not applicable.
[b] Number of days after the last spray. The first spray is always 21 days after peak bloom (Table 2-4), the '1st' indicates the interval how many days after the previous spray it was applied.
[c] The percent reduction of the mean of unprotected days across all years and stations compared to the 21-day schedule using the traditional spray parameters.

The improved protection given by the optimized schedule is due to a better distribution of copper applications over time. The average bloom schedule got the greatest benefit because in the 21-day schedule the last spray (Table 2-4) would provide most of its protection outside the proposed vulnerability period which extends until end of July. These results show how a variable interval spray schedule can increase the fruit protection by distributing the residue more evenly according to the rainfall pattern and vulnerability pressure.

Table 3-5. Schedules resulting from the variable concentration optimization algorithm. These results consider all years of available weather data and all locations average, the worst-case scenario as plant parameters and typical spray volume and concentration and 21-day application schedule.

Peak Bloom	Concentration of spray[b]						Average of unprotected days per year/station	Reduction %[c]
	1st	2nd	3rd	4th	5th	6th		
Early	0.75	0.55	0.75	0.95	0.95	0.55	2.1	11.6
Average	0.85	0.55	0.85	0.95	0.75	0.55	2.7	13.6
Late	0.75	0.65	0.85	0.95	0.55	NA[a]	3.5	7.5

[a] Not applicable.
[b] Copper concentration of each spray including the first one after peak bloom (Table 2-4).
[c] The percent reduction of the mean of unprotected days across all years and stations compared to the 21-day schedule using the traditional spray parameters.

However, it is important to keep in mind that the optimized schedules are an empirical analysis of the copper residue influenced by past rain distribution. Consequently, in the majority of years, the optimized schedule will perform better, but there can be years in which the benefit will be minimal.

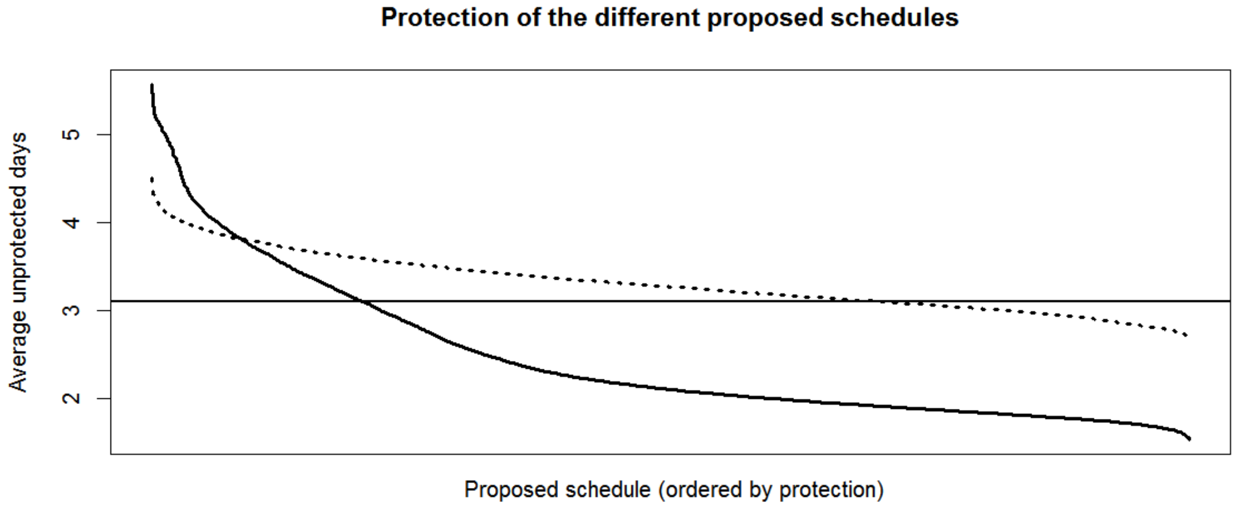

Figure 3-11. Plot the average unprotected days of each schedule produced by both interval optimization (continuous line) and concentration optimization (dashed line) for the average bloom date scenario. The horizontal line marks the average protection of the traditional approach of 21 days interval and 0.84 kg ha^{-1} (0.75 lb ac^{-1}) concentration for all copper applications. Each mark in the x-axis corresponds to one simulated optimization.

The concentration optimization has less satisfactory results as shown in Figure 3-11. Increasing the concentration of the applications has diminishing effects with larger values consequently reducing the margin for improvement. It is also possible to see how inadequately planned schedules can greatly decrease the protection. The worst tested schedules had an increase of more than 100% in the number of unprotected days.

CHAPTER 4
CONCLUSIONS

The citrus copper application scheduler, a web-based decision support system, enables citrus growers to easily access information to make decisions concerning the timing of copper applications. By using the web-based tool, growers can reduce copper applications in dry years and minimize unprotected periods in wet years. The results of the copper model with a threshold of 0.25 $\mu g\ cm^{-2}$ and historical weather data showed that the traditional 21-day schedule at recommended copper application rates did not provide enough residual copper to protect groves in wet years. Conversely, it was shown that it is possible to avoid unnecessary copper applications in dry years by optimizing the timing of the sprays.

Two approaches for optimizing the copper schedules were proposed with the objective of evenly distributing the copper protection according to the historic weather data. The optimized schedule with varying intervals between applications was able to attain 50% fewer unprotected days for the simulated period using the average bloom date scenario. The optimized schedules with varying concentrations provide an alternative for producers, who must have a fixed interval spray schedule, but it provides smaller gains in protection.

Lastly, this study provides a documentation of the algorithm used in the source code of the copper model as well as a study of the model sensitivity to change in parameters. It was found that the current recommendations for spray volume and concentration are a good tradeoff between protection and amount of copper applied.

As future developments, there exists an ongoing effort for allowing the user to automatically use the Real-Time Mesoscale Analysis (RTMA, http://www.nco.ncep.noaa

.gov/pmb/products/rtma) rainfall data for a producer's specific area instead of using FAWN weather stations. Since RTMA is calculated on a 5-km wide grid, it would likely have more precise rainfall information when the grove is distant from a weather station. Also, the fruit growth functions for the model end in early July. With the arrival of citrus canker and black spot, copper applications are needed throughout the summer. Fruit growth and copper residue loss data are being gathered. These data will be used to improve the residue predictions from July to October and be added to the model.

APPENDIX
COPPER RESIDUE MODEL TRANSLATED TO R

```
# Translated from Java to R by Tiago Zortea

# Tiago Zortea (zortea@ufl.edu )

# 05/16/2011

# The comments are from the original Java code

toJulian = function (pdate){

   pdate=as.POSIXlt(pdate)

   return(pdate$yday + 1)

}

residue = function(init_depo, daysAfterBloom, model){

    # convert to ug/cm2

    return (init_depo/area(daysAfterBloom, model))

}

init_depo = function (volume, concRatio, sprayDate, bloomDate, model){

    # compute initial deposition from spray volume and concentration

    # unit: ug = ug / cm2 * cm2

      inside=T # 1 for insider 2 for outsider

      if(inside){

            if(volume < 125) return ((0.7167 + 0.058 * volume) *

            area(sprayDate - bloomDate, model) * concRatio)

            else if(volume >= 125 && volume <=  250) return ((9 - 0.01133 *

            volume) * area(sprayDate - bloomDate, model) * concRatio)

            else return ((6 + .0022*volume) * area(sprayDate - bloomDate,

            model) * concRatio)

      } else {

            if (volume < 125) return ((0.5792 + 0.08017 * volume) *

            area(sprayDate - bloomDate, model) * concRatio)

        else if(volume >= 125 && volume <= 250) return ((13 -
```

```
            0.016 * volume) * area(sprayDate - bloomDate, model) * concRatio)
        else return ((11 - .0078 * volume) * area(sprayDate -
            bloomDate, model) * concRatio)
      }
}
reduceRatio = function(rain){
      if (rain >= 0 && rain <= 0.5) return (.48 * rain)
    if (rain > 0.5 && rain <= 2) return (.12 * (rain - 0.5) + .24)
    return (0.42)
}
area = function (daysAfterBloom, model){
    if (tolower(model) == "grapefruit")
        return (gompertz(daysAfterBloom,73,22650,0.0220))
    if (tolower(model) == "valencia")
        return (gompertz(daysAfterBloom,69,14949,0.0222))
      if (tolower(model) == "mandarin")
        return (gompertz(daysAfterBloom,77,14263,0.0198))
    if (tolower(model) == "navel")
        return (gompertz(daysAfterBloom,64,19856,0.0214))
      #Orange (generic, use valencia parameters)
      return (gompertz(daysAfterBloom,69,14949,0.0222))
}
residue = function(init_depo, daysAfterBloom, model){
    # convert to ug/cm2
    return (init_depo / area(daysAfterBloom, model))
}
gompertz =  function (daysAfterBloom, originalBloomDate, max, b){
    # Gompertz equation...
    #    AREA = MAX*EXP(LN(MIN/MAX)*EXP(-B*T))
```

```
    #
    #    AREA = fruit surface area in square millimeters
    #    T = date (julian, Jan 1 = 1)
    #    MIN = Minimum Size (always 0)
    #    MAX = Maximum Size (estimated for each experiment)
    #    B = parameter (estimated for each experiment)
    # originalBloomDate is date regression was based on
    # daysAfterBloom is days since bloom in current year
    # add to get adjusted julian date (accounts for the fact
    # that bloom date this year might not be same as bloom
    # date in original year)
    #                                  Max     B
    #Control Block/Yellow valencia       14949   0.0222
    #Shade/Pink valencia                 14611   0.0213
    #Plastic Block/Pink valencia         14763   0.0215
    #Control Block/Yellow grapefruit     22650   0.0220
    #Shade/Pink grapefruit               22733   0.0217
    #Plastic Block/Pink grapefruit       24116   0.0216
    #Fallglo                             14263   0.0198
    #Navel                               19856   0.0214
    julianDate = originalBloomDate + daysAfterBloom
    min = 0.000000000645   # very small
    return (max * exp( log(min / max) * exp(-1 * b * julianDate)))
}
simulateResidue = function(experiment) {
      sql = paste ("SELECT simID, CONVERT( scion, CHAR ) as scion ,
        bloom_date FROM simCtrl WHERE simID=",experiment)
      rs = dbSendQuery(con,statement=sql)
      experimentPar = na.omit(fetch(rs,n=-1))
```

```
experimentPar[,'bloom_date']=toJulian(experimentPar[,'bloom_date'])
sql = paste ("SELECT date , inches FROM simRain WHERE simID=",
  experiment," order by date")
rs = dbSendQuery(con,statement=sql)
experimentRain = na.omit(fetch(rs,n=-1))
experimentRain$date=toJulian(experimentRain[,1])
sql = paste ("SELECT date, volume, concentration FROM simSpray
  WHERE simID=",experiment," order by date")
rs = dbSendQuery(con,statement=sql)
experimentSprays = na.omit(fetch(rs,n=-1))
experimentSprays$date=toJulian(experimentSprays[,1])
concRatio = experimentSprays[1,'concentration'] / 4
startDate=experimentSprays[1,'date']
scion=experimentPar[1,'scion']
results=rep(0,366)
depo =init_depo(experimentSprays[1,'volume'],concRatio,
  startDate,experimentPar[1,'bloom_date'],scion)
results[1]=residue(depo,startDate-experimentPar[1,'bloom_date'],scion)
change=0
for (x in 2:366){
      idx=which.max(match(experimentRain$date,startDate + (x - 1)))
      if(length(idx)>0){
            change = -reduceRatio(experimentRain[idx,'inches']) * depo;
      }
      idx=which.max(match(experimentSprays$date,startDate + (x - 1)))
      if(length(idx)>0){
            concRatio = experimentSprays[idx,'concentration'] / 4
            change =init_depo(experimentSprays[idx,'volume'],concRatio,
            experimentSprays[idx,'date'],
```

```
                experimentPar[1,'bloom_date'],scion)
            }
        # rainfall occurs, Cu reduced, re-calculate the coefficient of
        # the exp function: data=new_co * e ^ (x) (x-starts from zero...)
        depo=depo + change
            results[x]=residue(depo,startDate + (x -
            1) - experimentPar[1,'bloom_date'],scion)
        change = 0;
      }
      return(results)
}
```

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BIOGRAPHICAL SKETCH

Tiago Zortea was born in Passo Fundo, Brazil on October, 1983. He obtained an Associate's degree in Electronics from the Cecy Leite Costa Institute along with his high school degree in 2004. After, he enrolled in the Electrical Engineering program at University of Passo Fundo, but soon he realized his real passion was in the computing sciences. In 2005, he changed his major to Computer Science obtaining the degree of Bachelor's of Computer Science in 2011. To be able to afford the high educational costs, he began searching for a job as soon as he began his college studies. Still in 2005, he started working as Assistant Developer at the Caixa Federal Bank. In 2007, he was hired by Compasso S.A. as a Java web developer. In Compasso he quickly ascended positions; by 2011 he was a Senior Software Engineer leading a team of developers. Even though he had a fulfilling job by this time, Tiago wanted to be able to exercise his scientific knowledge also, for that matter he contacted his advisor Dr. Willingthon Pavan. His advisor, who had attended University of Florida as a research scholar, contacted Dr. Clyde Fraisse which ultimately led to a position offer to Tiago as research scholar at University of Florida. In 2011, Tiago was offered a full assistantship to pursue his graduate education at the Agricultural and Biological Engineering Department at University of Florida, under the supervision of Dr. Clyde Fraisse.