Epidemiology of Citrus Diseases

Megan Dewdney
PLP 5115c
What is Epidemiology?

- The study of epidemics
  - Change in disease intensity in a host population over time and space
- Change: often an increase
  - Dynamic process
- Disease: dealing with the ‘disease’, not just pathogen or crop (plant)
  - Citrus canker rather than Xanthomonas citri subsp. citri
  - Huanglongbing rather than Ca. Liberibacter asiaticus
What is Epidemiology? cont.

- **Host**: Organism (potentially) infected by another organism
  - *Alternaria Brown spot*: Tangerines and tangerine hybrids
- **Population**: A population phenomena of both host and pathogen
  - Dynamic processes often described with statistics or mathematical models
- **Time and Space**: Two dimensions of interest
  - Change over time or over a grove and sometimes both
Many Levels to Study Organisms

Molecular
Cellular
Tissue
Organ
Individual
Population
Community
System

Epidemiology
« Science of disease in populations »
(Vanderplank, 1963)
Broad Definition

- **Epidemic does NOT mean widespread or high levels of disease**
  - Pandemic is the correct term for widespread or high levels of disease

- **Example:** *Phytophthora infestans* (Potato Late Blight)
  - Field with 4 million plants ($4 \times 10^6$)
  - 1 lesion/plant = 0.1% severity ~ 1/1000 leaf surface covered by lesions
  - Limit of detection

LV Madden
Late Blight Example cont.

- time \( t = 0 \) days \( d \) disease severity \( y = 0.1\% \) → \( t = 90 \) days \( d \) \( y = 100\% \)
  - 1000 fold change
- \( t = 30 \) days \( d \) \( y = 1\% \) → \( t = 90 \) days \( d \) \( y = 100\% \)
  - 100 fold change
- \( t = 0 \) days \( d \) \( y = 1 \) lesion/field \( (0.1/4 \times 10^6) \) → \( t = 90 \) days \( d \) \( y = 100\% \)
  - \( y = 1 \) lesion/plant \( (0.1\% \text{ severity or } 1/4 \times 10^6 \text{ lesions/field}) \) – \( 4 \times 10^6 \) fold change
Late Blight Example cont.

- How to determine when the epidemic started?
- Does scale change the biological processes that occur?
- Change in population disease intensity is an epidemic
Disease Triangle

- Ecology of disease
- Principle of disease triangle still relevant but on population level
  - Emphasis on interactions
- Time or space or humans or vectors?
  - Awkward since limited to 3 dimensions

Epidemiology can be either...

- **Descriptive**
  - Where; when; what
  - Has been used to fill in disease cycles
  - **OR**

- **Quantitative**
  - How many ‘propagules’ are needed
  - How much disease is present
  - How fast does disease develop
  - How far can propagules travel
Tool Box

- Classical plant pathology
  - Culturing, microscopy, Koch’s postulates...

- Techniques from complimentary fields
  - Agronomy, botany, ecology, entomology, genetics, statistics, mathematics, meteorology etc.
Host Growth and Susceptibility

- Melanose control requires good coverage with fungicide on the fruit surface for nearly 3 months
- Copper is most common fungicide
  - Does not redistribute well on plant surface
  - Has good residual activity
  - Can build up in soil
  - Phytotoxicity
- Foreseen problems?
Host Growth and Susceptibility

- Field study conducted to compare number of applications with same amount of copper
- More sprays reduced disease
  - Covered up areas on fruit exposed by growth
  - Less wash off

<table>
<thead>
<tr>
<th>Product</th>
<th>No. of applications</th>
<th>1995</th>
<th>1996</th>
<th>1997</th>
<th>Marketable fresh (%)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Kocide</td>
<td>0</td>
<td>2.5</td>
<td>1.6</td>
<td>3.0</td>
<td>11 c</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.4</td>
<td>1.0</td>
<td>1.8</td>
<td>61 b</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.5</td>
<td>1.0</td>
<td>1.9</td>
<td>60 b</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.4</td>
<td>1.1</td>
<td>1.5 bc</td>
<td>61 b</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.1</td>
<td>0.9</td>
<td>1.2</td>
<td>79 a</td>
</tr>
<tr>
<td>Champ</td>
<td>1</td>
<td>1.7</td>
<td>1.0</td>
<td>...</td>
<td>48 cd</td>
</tr>
<tr>
<td>Formula II</td>
<td>2</td>
<td>1.7</td>
<td>1.1</td>
<td>...</td>
<td>47 cd</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.8</td>
<td>1.0</td>
<td>...</td>
<td>43 d</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.6</td>
<td>1.0</td>
<td>...</td>
<td>54 bc</td>
</tr>
</tbody>
</table>

*Timmer et al, 1998*
Host Growth and Susceptibility

- Copper residue can vary by year depending on rain
- Model developed to account for growth and rain

Table 2. Effect of fruit growth and rainfall on the copper residues remaining on fruit after application of fungicides

<table>
<thead>
<tr>
<th>Product</th>
<th>Sample date</th>
<th>Rainfall (mm)$^1$</th>
<th>Fruit surface area (cm$^2$)$^a$</th>
<th>Metallic Cu residue</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mg/fruit$^v$</td>
<td>µg/cm$^2$ fruit surface$^w$</td>
<td></td>
</tr>
<tr>
<td>Kocide 2000$^b$</td>
<td>1 May 96</td>
<td>0</td>
<td>138 ± 19</td>
<td>1.93 ± 0.45 (100)</td>
<td>13.9 ± 1.9 (100)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 May</td>
<td>39</td>
<td>382 ± 72</td>
<td>1.48 ± 1.40 (77)</td>
<td>4.4 ± 4.2 (32)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>29 May</td>
<td>48</td>
<td>587 ± 105</td>
<td>1.03 ± 0.35 (33)</td>
<td>1.7 ± 0.4 (12)</td>
<td></td>
</tr>
<tr>
<td>Champ Formulia II$^y$</td>
<td>1 May 96</td>
<td>0</td>
<td>78 ± 33</td>
<td>0.99 ± 0.53 (100)</td>
<td>13.3 ± 6.0 (100)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 May</td>
<td>39</td>
<td>373 ± 65</td>
<td>0.60 ± 0.82 (61)</td>
<td>1.6 ± 2.1 (12)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>29 May</td>
<td>48</td>
<td>631 ± 118</td>
<td>1.04 ± 0.37 (102)</td>
<td>1.7 ± 0.6 (13)</td>
<td></td>
</tr>
<tr>
<td>Kocide 2000$^b$</td>
<td>6 May</td>
<td>0</td>
<td>308 ± 102</td>
<td>1.33 ± 1.03 (100)</td>
<td>5.6 ± 1.4 (100)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 May</td>
<td>0</td>
<td>374 ± 29</td>
<td>0.55 ± 0.26 (30)</td>
<td>1.4 ± 0.7 (25)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 June</td>
<td>47</td>
<td>552 ± 36</td>
<td>0.36 ± 0.21 (20)</td>
<td>0.6 ± 0.4 (11)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18 June</td>
<td>163</td>
<td>495 ± 27</td>
<td>0.13 ± 0.08 (7)</td>
<td>0.3 ± 0.2 (5)</td>
<td></td>
</tr>
</tbody>
</table>

$^1$ Total rainfall since the application of fungicide.

$^a$ Fruit surface area ± standard deviation.

$^v$ Total copper residue per fruit in mg ± standard deviation. Numbers in parentheses are the percentages of initial residue remaining.

$^w$ Copper residue per cm$^2$ of fruit surface ± standard deviation. Number in parentheses are the percentages of the initial residue.

$^b$ Applied on 30 April 96 at 9.1 kg metallic copper/ha.

$^y$ Applied on 30 April 96 at 4.5 kg metallic copper/ha.

$^x$ Applied 5 May 97 at 4.5 kg metallic copper/ha.

Timmer et al, 1998
Host Growth and Susceptibility

- With no rain, copper residues will decline quickly with rapid growth in early season
- Rain accelerates the process
- Melanose cannot infect fruit > 8 cm dia.
Host Growth and Susceptibility

- Size classes for fruit diameter
  - 1 = 20-25 mm, 2 = 26-35 mm, 3 = 36-40 mm, 4 = 41-60 mm, 5 > 60 mm

- Lesion ratings
  - 0 = no lesions, 1 = discrete lesions within water-soaked (WS) area, 2 = coalesced lesion within WS area, 3 = coalesced lesion within and without WS area, 4 = expansion of lesions beyond 3 rating

Graham et al, 1992
Host Growth and Susceptibility

- Cultivar susceptibility and age related or ontogenic resistance affects epidemic
- Which fruit is most susceptible?
- As fruit become larger less susceptible
- Time is also a factor

Graham et al, 1992
Host Growth and Susceptibility

- Why do fruit become more then less susceptible?
  - Similar phenomenon in leaves

  - Stomates opening as fruit become larger?
  - *Xanthomonas citri* subsp. *citri* may need expanding tissue to be able to infect
    - Grapefruit expands for longer during the season?
  - Surface waxes may not allow for as much wetting
Fruit Growth

Does Grapefruit expand for longer?
Stomates and Canker

- It was thought that stomate size and density would affect canker severity
  - But no relationship
- Host susceptibility on leaves
  - Other factors
  - Not yet understood

**TABLE 1. Characteristics of stomata on leaves of two-thirds and full expansion of field-grown citrus cultivars varying in susceptibility to citrus canker**

<table>
<thead>
<tr>
<th>Cultivar*</th>
<th>Large stomata</th>
<th>Two-thirds expansion</th>
<th>Small stomata</th>
<th>Large Stomata</th>
<th>Full expansion</th>
<th>Small stomata</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (μm²)</td>
<td>Area (μm²)</td>
<td>Density (no./0.059 mm²)</td>
<td>Open (%)</td>
<td>Area (μm²)</td>
<td>Density (no./0.059 mm²)</td>
</tr>
<tr>
<td>Red Blush grapefruit</td>
<td>46.5 a</td>
<td>13.4 a</td>
<td>48.0 a</td>
<td>65.0 a</td>
<td>61.8 b</td>
<td>28.2 bc</td>
</tr>
<tr>
<td>Marsh grapefruit</td>
<td>37.8 ab</td>
<td>4.5 c</td>
<td>30.3 b</td>
<td>34.2 bc</td>
<td>60.7 b</td>
<td>25.9 c</td>
</tr>
<tr>
<td>Swingle citruselo</td>
<td>35.1 ab</td>
<td>10.1 b</td>
<td>33.9 b</td>
<td>24.8 c</td>
<td>90.9 b</td>
<td>29.4 bc</td>
</tr>
<tr>
<td>Valencia sweet orange</td>
<td>45.2 a</td>
<td>9.9 b</td>
<td>45.0 a</td>
<td>54.4 a</td>
<td>59.9 b</td>
<td>38.6 a</td>
</tr>
<tr>
<td>Orlando tangelo</td>
<td>28.5 b</td>
<td>6.1 c</td>
<td>49.2 a</td>
<td>21.9 cd</td>
<td>50.9 b</td>
<td>32.0 b</td>
</tr>
<tr>
<td>Sour orange</td>
<td>22.6 b</td>
<td>3.7 c</td>
<td>32.4 b</td>
<td>10.2 d</td>
<td>41.7 b</td>
<td>21.2 d</td>
</tr>
<tr>
<td>Cleopatra mandarin</td>
<td>27.2 b</td>
<td>4.0 c</td>
<td>34.8 b</td>
<td>38.0 b</td>
<td>62.6 b</td>
<td>31.3 b</td>
</tr>
</tbody>
</table>

* Cultivars are listed in descending order of susceptibility to citrus canker based on artificial inoculations and field observations.

* Area of the opening of antichambers (see Fig. 1).

* Percentage of stomata with open antichambers (see Fig. 1).

* Means (of 10 fields, each measuring 0.059 mm²) in columns followed by the same letter do not differ significantly according to the Student-Newman-Keuls multiple range test (P ≤ 0.05).
Host Growth and Susceptibility

- Citrus leaves grow too fast to be effectively protected by available fungicides
  - Pyraclostrobin, copper hydroxide, ferbam
  - Example is the case of Alternaria brown spot
  - Similar for Melanose and Citrus Scab

Mondal et al., 2007

S = sprayed
I = inoculated
% = increase of leaf area between 2 dates

![Graph showing disease control and leaf growth]
Environment
Environment

- Can affect whether a pathogen will infect
  - *Alternaria alternata* and *Xanthomonas citri* subsp. *citri* cannot infect if it is dry
- Pathogen dispersal is affected by environment
  - *Diaporthe citri* conidia are distributed by rain
- Environment influences inoculum production
  - *Mycosphaerella citri* pseudothecia require wetting and drying cycle to be initiated and mature
- Other examples?
Wind

- Tricky to work with in lab!

Gottwald and Graham, 1992
Effect of Wind on Canker

- This is how it was determined that 8 m/s (18 mph) of wind driven rain was needed to force *X. citri* subsp. *citri* cells into a leaf
- Leaf expansion was also important
  - Why?
Effect of Wind on Canker

- Pressure also affected number of bacteria in leaves

- What is the difference in the two leaf surfaces?
What Environmental Stimulus is Needed?

- Many environmental stimuli were tested to see when *A. alternata* spores were released
  - Inside artificial chamber

Timmer et al., 1988
Environmental Stimuli cont.

- Rain and drops in relative humidity are not clearly distinguishable but both contribute to spore release.
- In field conidia production and infection weakly associated with leaf wetness duration.

Timmer et al., 1988
When are Conidia Produced?

- Field spore trapping of *Pseudocercospora angolensis*
  - Relationship with temperature and rainfall more evident
  - Similar pattern with relative humidity
  - Interactions between variables not tested

Pretorius, 2005
Infection Conditions: Alternaria Brown Spot

- Optimum temperatures 23-27°C
  - Can get infection between 17-32°C
- Infection can occur with as little as 4-6 hours of leaf wetness but disease severity increases with leaf wetness
- Are there other factors that could affect this relationship?

Canihos et al., 1999
Infection Conditions Complicated by Host

- Not all cultivars react to the same infection conditions identically
  - All susceptible hosts
  - Nova needs > 30 hours of leaf wetness to have same level of infection as Minneola at 15 hours

Mondal et al. 2008
Probability of Disease

- Model developed from growth chamber data
- Prob.’s calculated for each lesion rating at the leaf wetness and temperature combination
Disease Probabilities cont.

- Probabilities change with cultivar
- Sunburst is much less susceptible than Dancy
- Reflected in graphs
Lots of Interest in Leaf Wetness and Temperature

- Conidia germinate
  - 6 hrs at 16 °C
  - 4 hrs 20 to 28 °C
- Literature has varying times and temperatures needed for infection
- Optimum temp determined to be 24-28 °C

Agostini et al., 2003
Infection Conditions for Scab

- Contradictory information in the literature about leaf wetness and temperature
  - Optimal temperature range
    ✓ 23.5 to 27 °C
  - Optimal leaf wetness
    ✓ Between 12 and 24 hrs

Agostini et al., 2003
Temperature Effect can Change with Disease Evaluation

- *Phytophthora palmivora* - which disease?
- What is the difference between incidence and severity?
  - Incidence – disease status of plant units as individual or pieces such as number of proportion of leaves with disease
  - Severity - area of disease
- How could this be important in an epidemic?

*Timmer et al.*, 2000
Leaf Wetness and Temperature also Important for Inoculum Production

- Sporangia production highly dependant on both factors
- Interaction also important

✓ What is the significance of an interaction?

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (Tp)</td>
<td>3</td>
<td>35.25</td>
<td>0.0001</td>
</tr>
<tr>
<td>Time (Tm)</td>
<td>4</td>
<td>79.85</td>
<td>0.0001</td>
</tr>
<tr>
<td>Tp × Tm</td>
<td>12</td>
<td>10.35</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Timmer et al., 2000
Pathogen Effects

○ Questions of interest about the pathogen:
  ○ What is required to produce inoculum?
    ✓ Are there environmental or other factors that contribute to inoculum production
  ○ How much inoculum is present?
    ✓ Can affect how quickly an epidemic can become established and move into exponential phases
  ○ When is the inoculum present?
    ✓ No inoculum; no disease
Spore Traps

Burkard Spore Trap
Allows for sampling spore patterns over time

Impact Traps/Volumetric
Allows for sampling spores in a volume of air but not over time

- Spores are counted under the microscope
- Can be tedious and requires training
- Some new versions allow for PCR identification
Ascospore Ejection Pattern

- *Phyllosticta* spp. ascospore ejection is reported to be triggered by rain
- In Brazil wetness duration was more important
- Very frequent rain events; ascospores cannot mature fast enough to eject with each rain event
- Cannot forecast infection event based on rainfall

Reis et al., 2006
**Phyllosticta spp. Ascospore Release in Florida**

**Week of May 13-20, 2010**

<table>
<thead>
<tr>
<th>Date</th>
<th>Mon 17</th>
<th>Wed 19</th>
<th>Fri 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Guignardia ascospores</td>
<td>0</td>
<td>125</td>
<td>300</td>
</tr>
</tbody>
</table>

**Rain (inches)**

| 0.0 | 0.2 | 0.4 |
| 0.6 | 0.8 | 1.0 |

**Temperature (F)**

| 65 | 70 | 75 |
| 80 | 85 | 90 |
| 95 | 100 | 105 |

**Week of May 21-28, 2010**

<table>
<thead>
<tr>
<th>Date</th>
<th>Fri 21</th>
<th>Sun 23</th>
<th>Tue 25</th>
<th>Thu 27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Guignardia ascospores</td>
<td>0</td>
<td>50</td>
<td>225</td>
<td>175</td>
</tr>
</tbody>
</table>

**Rain (inches)**

| 0.0 | 0.1 | 0.2 |
| 0.3 | 0.4 | 0.5 |
| 0.6 | 0.7 | 0.8 |

**Temperature (F)**

| 65 | 70 | 75 |
| 80 | 85 | 90 |
| 95 | 100 | 105 |
Pathogen Populations

- How many nurseries have metalaxyl resistant isolates of *Phytophthora nicotianae*?
- What proportion of the population?
- If nurseries have resistant isolates can spread around state

Table 1. Survey of Florida citrus nurseries to determine the prevalence of metalaxyl-resistant isolates of *Phytophthora nicotianae*

<table>
<thead>
<tr>
<th>Nursery operations</th>
<th>Site</th>
<th>Phytophthora control program</th>
<th>No. of blocks sampled</th>
<th>Propagules/cm³</th>
<th>Metalaxyl-resistant (%)²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immokalee</td>
<td>1</td>
<td>B</td>
<td>7</td>
<td>52</td>
<td>0-128; 55</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>A</td>
<td>6</td>
<td>90</td>
<td>0-152; 58</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>A</td>
<td>2</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>La Belle I</td>
<td>1</td>
<td>A</td>
<td>5</td>
<td>58</td>
<td>0-126; 51</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>A</td>
<td>6</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>La Belle II</td>
<td>1</td>
<td>A</td>
<td>5</td>
<td>58</td>
<td>0-126; 51</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>A</td>
<td>6</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>Florida</td>
<td>D</td>
<td></td>
<td>8</td>
<td>9</td>
<td>0-66; 0</td>
</tr>
<tr>
<td>Lake Placid</td>
<td>D</td>
<td></td>
<td>8</td>
<td>10</td>
<td>0-26; 0</td>
</tr>
<tr>
<td>Sebring</td>
<td>C</td>
<td></td>
<td>5</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>Avon Park I</td>
<td>A</td>
<td></td>
<td>8</td>
<td>48</td>
<td>0-104; 35</td>
</tr>
<tr>
<td>Avon Park II</td>
<td>1</td>
<td>B</td>
<td>11</td>
<td>20</td>
<td>0-58; 31</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>B</td>
<td>7</td>
<td>18</td>
<td>0.70; 54</td>
</tr>
</tbody>
</table>

³ A = metalaxyl used exclusively; B = metalaxyl and fosetyl-Al alternated; C = fumigation only; D = fumigation and metalaxyl and fosetyl-Al alternated.

² Percentage of isolates able to grow on media containing 1.0 µg/ml of metalaxyl.

Timmer et al. 1998
Are Metalaxyl Resistant Isolates as Fit as Sensitive Ones?

- Roots: similar proportion found as added
  - Resistant slightly more
- Soil: more resistant propagules than sensitive
  - More propagules recovered than applied (RYT)
- Resistant strain more aggressive – more likely to spread

Timmer et al., 1998
Bacterial Dynamics

- Very few bacteria need to penetrate leaves to initiate an infection
- In 1 week have $10^7$ cells in a lesion
  - Many propagules formed!
  - This is relatively slow for bacteria

Graham et al., 1992
Greasy Spot Inoculum Production

- Wetting is critical for pseudothecia production
- Most ascospores produced with the 3-day per week wetting scheme
- Wetting scheme also changes peak ascospore ejection
Optimal Temperatures for Ascospore Production

- Spores trapped with a Burkhard trap
  - Spores are produced within tight temperature range
  - Somewhat unusual but in Florida conditions are within the optimal range often

Mondal and Timmer, 2002
Statistics and Mathematics

○ Much of epidemiology uses statistics especially the quantitative work
○ Much of the theoretical modeling that is undertaken uses a combination of mathematics and statistics
○ A good working knowledge of statistics is needed to be a good epidemiologist and/or ecologist
  ✓ At least know when to collaborate!
Disease Progress over Time

- Time is a fundamental factor in an epidemic since we are usually measuring change in disease status over time
  - Not a static process
  - Why some people include time in the disease triangle
- Often disease progress curves used to compare epidemics
Disease Progress of Canker Epidemic

- Disease progress curves at 5 urban sites
  - A is cumulative data
  - B is the rate of change between each time point
- Can see this is a very dynamic process as the rate of disease is not continuous

Gottwald et al, 2002
Epiphytic Growth and Severity

- Greasy spot severity is influenced by when the epiphytic growth of *Mycosphaerella citri* occurs.

- The severity that occurs with levels of epiphytic growth changes over time.
  - Disease severity does not track epiphytic growth especially in the winter.

Mondal and Timmer, 2003
Disease Progress in Space

- There are two aspects of general interest
  - Dispersal gradients
  - Spatial patterns
- Dispersal gradients tell how far an organism can spread
- Spatial patterns can give a sense of how the organism spreads
  - Splash, wind, vector etc.
  - Can indicate unforeseen dynamics in diseases
How Far Can A Sporangia Splash?

- Depends on species
  - \( P. \textit{palmivora} \) splashes further than \( P. \textit{nicotianae} \)
- Some strains travelled further than others
- Means that \( P. \textit{palmivora} \) is more likely to move by splash and spread further

Timmer \textit{et al.}, 2000
Horizontal and Vertical Movement

- *Phytophthora palmivora* travels in 2 dimensions with water droplets

- Appears that majority of sporangia travel down
  - Greater number of colonies/sporangia below inoculum source

Timmer *et al.*, 2000
Canker Frequency and Distance

- Tried to find a distance where it was unlikely an infected tree escaped
  - $579 \text{ m} = 1900 \text{ ft}$

Gottwald et al, 2002
Common Spatial Patterns

**Uniform**
Evenly spaced pattern
Unusual in biological systems
Sometimes from some sort of application mistake

**Random**
Occurs if disease process is independent of neighbors

**Aggregated**
Occurs when the disease process depends on distance among individuals
How Many Samples Do I Need?

- Want an accurate estimate of pathogen population
- Need to know whether the pathogen is common
- From the patterns (with several equations) arrived determined that:
  - 1, 2, 3, 4, 5 or ten samples/tree were taken then needed to sample 22, 13, 10, 8, 7 or 5 trees respectively

Timmer et al., 1998
Urban Citrus Canker

- What sort of pattern is this?
- Note how few trees were affected initially

Gottwald et al, 2002
Citrus Scab Spread from a Foci

Gottwald, 1995
What Type of Spread Occurs with HLB

- Wanted to know if spread was from tree to tree in grove or from outside grove
- Used stochastic modeling to develop plots
  - MCMC posterior densities
- These plots show most spread was mainly background (outside)

Gottwald et al, 2008
Spread Within Grove

- Spread was mid-range distance so not spreading to nearest neighbors but to nearby trees

Gottwald et al, 2008
What Kind of Spread is Occurring Here?

Gottwald et al, 2008
Spatial Patterns

- Could see with both Canker and Scab that the most likely trees to be infected were near by
- Scab is splash distributed
- Canker moves with wind-driven rain
- Also useful for understanding vectored diseases
  - There is both external and medium range movement of infectious Asian citrus psyllids
Disease Forecasting

- Two disease forecasting models used in citrus
  - Alter-Rater
  - Post-bloom Fruit Drop

- Designed so that the most effective timing of spray applications can be used

- Also predict decay of copper residue on fruit surfaces
ALTER-RATER: A Forecasting System

- Weather-based point system to better time fungicide applications
- Points assigned based on:
  - Rain fall and leaf witeness
  - Average daily temperature
- Thresholds vary by cultivar susceptibility
- Has been integrated into FAWN weather system
# The ALTER-RATER

## Suggested Threshold Scores

<table>
<thead>
<tr>
<th>Score</th>
<th>Situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>Heavily infested Minneola, Dancy, Orlando, Sunburst; Many flatwood groves, east coast, and SW Florida.</td>
</tr>
<tr>
<td>100</td>
<td>Moderately infested Minneola or Dancy, many Murcotts; Ridge and north Florida groves.</td>
</tr>
<tr>
<td>150</td>
<td>Light infestations, any variety, mostly Ridge and north Florida groves.</td>
</tr>
</tbody>
</table>
## ALTER- RATER Daily Points

<table>
<thead>
<tr>
<th>Rain &gt; 0.1 inch</th>
<th>LW &gt; 10 hr</th>
<th>Avg daily Temp</th>
<th>Assigned score</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>+</td>
<td>68-83</td>
<td>11</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>&gt; 83</td>
<td>8</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>&lt; 68</td>
<td>6</td>
</tr>
<tr>
<td>+</td>
<td>_</td>
<td>68-83</td>
<td>6</td>
</tr>
<tr>
<td>+</td>
<td>_</td>
<td>&gt; 83</td>
<td>4</td>
</tr>
<tr>
<td>+</td>
<td>_</td>
<td>&lt; 68</td>
<td>3</td>
</tr>
<tr>
<td>_</td>
<td>+</td>
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<td>6</td>
</tr>
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<td>_</td>
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<td>&gt; 83</td>
<td>6</td>
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<tr>
<td>_</td>
<td>+</td>
<td>&lt; 68</td>
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<tr>
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<td>_</td>
<td>_</td>
<td>&gt; 83</td>
<td>0</td>
</tr>
<tr>
<td>_</td>
<td>_</td>
<td>&lt; 68</td>
<td>0</td>
</tr>
</tbody>
</table>
Original PFD Model

\[ y = -13.63 + 1.16\sqrt{TD} + 0.48\sqrt{R \times 2500} + 1.77\sqrt{LW \times 5} \]

\( y \) = Percentage of flowers infected 4 days in the future
\( TD \) = total number of infected flowers on 20 trees; however if \( TD < 75 \) then \( TD = 0 \)
\( R \) = rainfall total for the last 5 days in inches
\( LW \) = Average number of hours of leaf wetness daily for the last 5 days - 10 hours
When to Follow the Model

A fungicide application is indicated if these three criteria are met:

1) the model predicts a disease incidence of greater than 20%
2) sufficient bloom is present or developing to represent a significant portion of the total crop
3) no fungicide application has been made in the last 10-14 days.
How the Citrus Copper Application Scheduler Operates

- Incorporates rainfall data from FAWN (Florida Automated Weather Network-www.fawn.ifas.ufl.edu) or own weather data
- Incorporates data on copper residue degradation
- Incorporates fruit growth size
Steps to Achieve Daily Prediction

Zortea et al. (2012)
Series of Equations

- Model is built on series of equations
  - Copper application residue
    \[ DEPO = (0.6399 + 0.005539 V)A \left( \frac{C}{4} \right) \]
  - Fruit growth
    \[ AREA = MAX \times e^{\ln\left(\frac{MIN}{MAX}\right)e^{-BT}} \]
  - Residue for each day
    \[ RESIDUE = \frac{DEPO}{AREA} \]
  - Residue loss
    \[ rLost = RESIDUE \left( 0.016535R \right) \]

Zortea et al. (2012)
To Use

- Select weather option and scion first

- Can use metric units
Enter Bloom Date

Bloom date: 03/18/2012
Every 21-day Schedule

- Have insufficient coverage for 6 days

- About perfect timing for third spray
Coverage Optimized with Model

- Moved first spray up 8 days
- Did not move third spray
Improvements in Progress

○ Some operations cannot easily take advantage of model
  ✔ Equipment movement
  ✔ Need to schedule in advance

○ Developed optimized schedule for such operations
  ✔ Historical weather per region
  ✔ Bloom date
Traditional Versus Optimized

- 21-day schedule (top) had 2 major gaps in coverage

- Optimized schedule reduced gaps in coverage but did not eliminate
Further Improvements

- Original model not designed to predict past mid July
  - Why?
- Need residue data for summer
- What diseases?
- Fruit growth too