Managing pest outbreaks through participatory iterative ecological forecasting

Chris Jones, Shannon Jones, Anna Petrasova, Vashek Petras, Devon Gaydos, Megan Skrip, Ben Seliger, Chelsey Walden-Schreiner, Yu Takeuchi, Ross Meentemeyer
Invasive Pests and Pathogens are Increasing Globally

$ > $billion annual cost

Increasing number of new invasives

*Each box represents ~500 new introduced species

Iterative Forecasting Improves Forecasts Steadily Over Time

Iterative Forecasting in Ecology:

We believe iterative ecological forecasting can help us improve our ability to model pest and pathogen spread.
Iterative Forecasting Improves Forecasts Steadily Over Time

Iterative Forecasting in Ecology:
We believe iterative ecological forecasting can help us improve our ability to model pest and pathogen spread.

Iterative Forecasting in Weather:
Improved accuracy with iterative forecasting
2020
1
2
3
4
5
6
7

today's 7-day forecast is as accurate as the 1-day forecast from 40 years ago
PoPS Forecasting Platform

Open-Source Model
- Modular
- Spatially explicit
- Dynamic

Spotted Lanternfly (Jones et al., 2021)
Sudden Oak Death (Jones et al., 2021, Gaydos et al., in press)
Citrus Greening
Spotted Lanternfly (Jones et al., 2021)
Porcine Epidemic Diarrhea Virus (Galvis et. Al., 2021)
Late Blight
Wheat Stripe Rust (Contina et al, in review)
Glassy Winged Sharpshooter
Spotted Lanternfly
Citrus Greening
Sudden Oak Death
Late Blight
PoPS Forecasting Platform
Porcine Epidemic Diarrhea Virus
Wheat Stripe Rust
Glassy Winged Sharpshooter
Future Pest/Pathogen

Database and Storage
• Forecasts
• All calibrated parameters and uncertainty
• Weather coefficient
• Host data
Spotted Lanternfly in Pennsylvania:
An example of iterative forecasting improvements

- Discovered in Berks County, PA in 2014
- Over 90 counties quarantined across 11 states
- $13+ Billion in crops and forest at risk
- Has spread to New Jersey, Delaware, Virginia, New York, Virginia, West Virginia, Ohio, Connecticut, Indiana, Rhode Island, Massachusetts, Vermont, and Maryland.

Sucks the sap out of branches and stems!
PoPS Forecasting Platform

(a) $\beta =$ Number of SLF dispersing from a single host under optimal conditions

(b) $\psi_{ijt} = \beta X_{it} P_{it} T_{it} I_{it} \cdot K(d_{ijt}, \alpha_1, \alpha_2, \omega, \tau) \cdot \frac{X_{jt} P_{jt} T_{jt} S_{jt}}{N_j}$

(c) **CONFUSION MATRIX FOR VALIDATION STATISTICS**

<table>
<thead>
<tr>
<th>PREDICTED</th>
<th>Positive (PP)</th>
<th>Negative (PN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive</td>
<td>True Positive (TP)</td>
<td>False Negatives (FN)</td>
</tr>
<tr>
<td>Negative</td>
<td>False Positives (FP)</td>
<td>True Negatives (TN)</td>
</tr>
</tbody>
</table>

- Accuracy $\frac{(TP+TN)}{T}$
- Precision $\frac{TP}{PP}$
- Recall/sensitivity $\frac{TP}{OP}$
- Specificity $\frac{TN}{ON}$
- Odds ratio $\frac{(TP+TN)}{(FP+FN)}$
Updating Parameters Based On New Data

\( \psi_{ijt} = \beta X_{it} P_{it} T_{it} I_{it} * K(d_{ij}, \alpha_1, \alpha_2, \nu, \omega, \kappa) * \frac{X_{jt} P_{jt} T_{jt} S_{jt}}{N_j} \)

(a) 2016 | 2017 | 2018 | 2019

- **\( \beta \)** = Number of SLF dispersing from a single host under optimal conditions
- **All species (N)**
- **Susceptible (S)**
- **Infested/infected (I)**
- **Seasonality (X)**
- **Precipitation (P)**
- **Temperature (T)**
Iteratively updating parameters improves forecast accuracy
PoPS Forecasting Platform Spatial Decision Support

Diagram showing interaction between geospatial computation, point cloud processing, 3D scanning, and projection, leading to GRASS GIS.
Improved Understanding of Temperature Influence

May - November

Early data on SLF temperature sensitivity

\[ \psi_{ijt} = \beta X_{it} P_{it} T_{it} * K(d_{ij}, \alpha_1, \alpha_2, \gamma, D(\omega, \kappa)) * \frac{X_{jt} P_{jt} T_{jt} S_{jt}}{N_j} \]
Improved Understanding of Temperature Influence

- Early data on SLF temperature sensitivity
- Updated SLF temperature sensitivity (based on new data)
Improved Understanding of Temperature Influence Increases Accuracy

Early data on SLF temperature sensitivity

Updated SLF temperature sensitivity (based on new data)

<table>
<thead>
<tr>
<th></th>
<th>Old Temp</th>
<th>Kreitman Temp Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>78.1 (3.1)</td>
<td>85.5% (2.1)</td>
</tr>
<tr>
<td>Precision</td>
<td>80.1 (3.7)</td>
<td>81.83% (3.7)</td>
</tr>
<tr>
<td>Recall/sensitivity</td>
<td>95.6 (1.7)</td>
<td>91.1% (1.8)</td>
</tr>
<tr>
<td>Specificity</td>
<td>61.3 (7.3)</td>
<td>80.8% (5.1)</td>
</tr>
<tr>
<td>Odds ratio</td>
<td>38.0 (.92)</td>
<td>43.26 (.97)</td>
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</tbody>
</table>
Adding New Model Features Based on Field Observations
Adding New Model Features Based on Field Observations

<table>
<thead>
<tr>
<th></th>
<th>Without Large Population Movements</th>
<th>With Large Population Movements</th>
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</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong> ((TP+TN)/T)</td>
<td>85.5% (2.1)</td>
<td>85.8% (2.0)</td>
</tr>
<tr>
<td><strong>Precision</strong> (TP/PP)</td>
<td>81.7% (3.8)</td>
<td>81.8% (3.7)</td>
</tr>
<tr>
<td><strong>Recall/sensitivity</strong> (TP/OP)</td>
<td>91.0% (1.9)</td>
<td>91.1% (1.8)</td>
</tr>
<tr>
<td><strong>Specificity</strong> (TN/ON)</td>
<td>80.7% (5.1)</td>
<td>80.8% (5.0)</td>
</tr>
<tr>
<td><strong>Odds ratio</strong> ((TP+TN)/(FP+FN))</td>
<td>43.25 (.98)</td>
<td>43.26 (.97)</td>
</tr>
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</table>

**CONFUSION MATRIX** FOR VALIDATION STATISTICS

<table>
<thead>
<tr>
<th></th>
<th>Positive (FP)</th>
<th>Negative (FN)</th>
<th>Observed Positives (OP=TP+FN)</th>
<th>Observed Negatives (ON=FP+TN)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OBSERVED</strong></td>
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<tr>
<td>Positive (%)</td>
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<tr>
<td>Positive (%)</td>
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<tr>
<td>False Positives (FP)</td>
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<tr>
<td>False Positives (FP)</td>
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<tr>
<td><strong>MODELED</strong></td>
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<tr>
<td>Modeled Positives (MP=TP+FP)</td>
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<td></td>
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<tr>
<td>Modeled Positives (MP=TP+FP)</td>
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<tr>
<td><strong>TOTALS</strong></td>
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<tr>
<td>Modeled Positives (MP=TP+FP)</td>
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<tr>
<td>Modeled Positives (MP=TP+FP)</td>
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</table>

**Statistics**: (Mean) (Standard Deviation)
PoPS Forecasting Platform Field Operations

(a) PoPS device
(b) Schematic of PoPS device
(c) Diagram showing components of PoPS device
(d) Graph showing temperature over time
(e) Image of PoPS device in use
(f) Images of PoPS device in different stages
(g) Images showing plant leaf samples

The PoPS device is a portable platform for forecasting field operations, using a smartphone and various components such as a LED, battery, lens, and LAMP cassette. It is designed to monitor and measure plant health and disease, as well as temperature changes, to predict and manage field operations effectively.
PoPS Forecasting Platform

Adaptive Management
- Make decisions
- Update system with management
- Update sampling locations

Detection Methods
- Traps
- Sensors
- Visual surveys

Field Observation and Scientific Feedback Loop

Pest or Pathogen Spread Model

PoPS Database
- Forecast Results and Metadata
- Priors and New Data
- Posteriors & Uncertainty

PoPS Forecasting Platform

PoPS Dashboard Interface
- User inputs
- User compares management scenarios
- Forecast results

Scenario Modeling Loop
- User inputs for scenario
- Forecast result

Participatory Feedback Loop
- Stakeholder feedback
- Workshops and stakeholder interactions

External Data
- Host Map
- Transportation
- Topography
- Weather

Calibration Loop
- Calibration
- Validation
- Sensitivity Analysis
- Posterior & Uncertainty

PoPS Forecasting Platform
Forecasting SOD Spread Spatial Decision Support
Forecasting SLF Spread Spatial Decision Support

30 APHIS personnel from science and technology, field operations, policy, and regulatory working groups on June 26, 2019
PoPS (Pest or Pathogen Spread) is a C++ library for a stochastic spread model of pests and pathogens in forest and agricultural landscapes. Performs a single time step of spread.

Main functions:
- generate
- disperse
- mortality
- remove

r.pops.spread

Parallelized GRASS GIS-wrapper that iteratively cycles through a series of time steps of the PoPS C++ model.

grasp-tangible-landscape (pops-steering branch)

Couples a physical Tangible Landscape model with r.pops.spread so that a user can physically add management and interact with the landscape.

r.pops

Parallelized R-wrapper that iteratively cycles through a series of time steps of the PoPS C++ model.

In addition to the forecast, this module also performs:
- Calibration
- Validation

Available as an R-package for end-users.

pops-model-api

Specialized Docker container designed to use Google Cloud Storage buckets and the database to store forecast inputs and outputs.

Calls r.pops.

PoPS-Dashboard-Platform

Front-end code for the PoPS interactive web dashboard interface and database.

Calls the model-api to run PoPS.

PoPS Database

PoPS Dashboard Interface

Tangible Landscape

Allows users to place physical management and run scenarios of PoPS.
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