The mango tree – blossom gall midge system: *in-silico* assessment of its functioning and management

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Introduction: context and issues

- Mango (Mangifera indica) is an important fruit crop
  - High economic and nutritional values
  - Produced in tropical and subtropical regions
  - Ranked 5th in the world (~ 50 M t / year)

- Mango is facing several production constraints, including yield losses due to pest and disease damages
  - Examples of damages on fruits and inflorescences:
    - Fruit flies
    - Stem and rot
    - Blossom gall midge
Growers are challenged to produce “more” and “better”

Which management practices, alternative to synthetic pesticides, can contribute to crop protection and reduce yield losses?

Our case study & objective

- A major pest damaging mango inflorescences: the **Blossom Gall Midge** (*Procontarinia mangiferae*)
- Develop a process-based modeling approach to **improve** our understanding of the crop-pest system functioning and its management using cultural practices
The mango blossom gall midge (BGM)

- BGM life-cycle on mango, its unique host-plant:

  - Females lay up to 150 eggs
  - Larval development (7 to 12 days)
  - Larvae leave the inflorescences and bury themselves into the soil
  - Larvae in diapause
  - Pupae development (4 to 6 days)
  - Adults emergence from the soil
  - Larvae in diapause from previous years
  - Life-span is 2 to 3 days

- Two management levers are investigated for pest control:
  1. **Soil mulching** used as physical barrier to break BGM life-cycle
  2. **Manipulation of mango phenology** to synchronize flowering and shorter the period of mango susceptibility

(From Amouroux, 2014)
2 Materiel and methods

- Experimental data
  - Collected in a mango orchard located in Reunion Island in 2017
  - Orchard split into three plots according to soil mulching treatments applied during the flowering period
  - Dynamics of inflorescences and larvae (assessed by trapping) in each of the three plots

- Synthetic mulching (woven plastic ground cover)
- Low weed cover
- High weed cover
Modeling framework

- Describes pest population dynamics in each plot, at a daily time-step during flowering, with inflorescence dynamics as input \( I_{t,i} \)
- Based on a representation of pest life-cycle:

\[
L_{t,i} = F_{t-d_{l,i}} \times (E_0 \mu_l) \times R
\]

\[
F_{t,i}^{\text{pup}} = L_{t-d_{p,i}} \times (\mu_{\text{soil}})^2 \times (p_p \mu_p) \times \frac{1}{1 + SR}
\]

\[
F_{t,i}^{\text{diap}} = D_{t,i} \times \mu_{\text{soil}} \times \frac{1}{1 + SR}
\]
Modeling framework: Main assumptions

- **H1**: female egg-laying lasts only 1 day

- **H2**: exogenous females are proportional to resource availability

- **H3**: female reproduction (egg-laying or survival) is limited by resource availability:
  \[ R = \min \left\{ k \frac{F_{t,i}}{I_{t,i}} \right\} \]

- **H4**: survival to the soil depends on mulching treatment:
  \[ \mu_{\text{soil}_L} \neq \mu_{\text{soil}_H} \text{ and } \mu_{\text{soil}_S} = 0 \]

- **H5**: the number of larvae in diapause (stock) and emergence dynamic \( f_D \) are the same in the three plots

- **H6**: between-plot movements of endogenous females are driven by resource availability and a “distance effect” (\( \delta \))

\[ F_{\text{endo}} = \frac{I_{t,i}(p_m \delta(i,j))}{\sum_{n \in \{i,j,k\}} I_{t,j}(p_m \delta(i,n)) F_{t,i}} \]

\[ 1/(1 + SR) = 0.5 \]

\[ p_p \mu_p = 0.77 \]

\[ D_{t,i} = f_D(t) \text{ stock} \]

with \( \sum_t f_D(t) = 1 \)
Model calibration and analysis

- **Calibration method:**
  - **Objective functions**: NRMSE between observed and estimated larvae numbers, assessed in each plot
  - **Optimization algorithm**: NSGA-II, a multi-objective and nondominated sorting genetic algorithm (Deb et al. 2002)
    - Subset of solutions converging near the Pareto-optimal front
  - **Hierarchical clustering** to identify groups in the set of nondominated solutions

- **Sensitivity analysis** based on a global approach with Sobol method (Saltelli et al. 2008)

- **Analysis of mango-BGM system functioning and management** with model-based hypotheses testing and *in silico* experiments
# Results

## Sensitivity analysis

- Main and total effects of the 7 parameters in each plot:

![Graph showing sensitivity analysis results](image)

- The model was mainly sensitive to parameters relative to:
  - Survival to soil mulching treatment ($\mu_{\text{soil}_L}$ and $\mu_{\text{soil}_H}$)
  - Reproduction capacity of females ($E_0 \mu$)
  - And secondarily, exogenous pest pressure ($\gamma$)
Assessing the contribution of different processes involved in pest population dynamics

Estimated number of larvae were broken down into 4 different origins:

- Exogenous females
- Endogenous females coming from the neighboring plots
- Endogenous females staying in the same plot - emerged from pupae
- Endogenous females staying in the same plot - emerged from larvae in diapause
Model solutions

3 types of solutions, involving different processes:

1. High number of exogenous females and emergence of females only in the plot L \( (\mu_{\text{soil L}}=0.97 \text{ and } \mu_{\text{soil H}}=0.05) \)

2. Absence of exogenous females and emergence of females only in the plot L \( (\mu_{\text{soil L}}=1 \text{ and } \mu_{\text{soil H}}=0.03) \)

3. Intermediate number of exogenous females and emergence of females in plots L and H \( (\mu_{\text{soil L}}=0.56 \text{ and } \mu_{\text{soil H}}=0.65) \)
The model captured general trends in population dynamics:

- Higher number of larvae in plots L and H (vs. plot S)
- Later increase in number of larvae in plots S and H (vs. plot L)

But it partly failed to capture others:

- Rapid decrease in number of larvae at the end of the season (for solutions 1 & 3)
- Decrease in number of larvae at the mid-season in plot L
How can the rapid population decrease at the end of the season be explained?

Model-based hypotheses testing:

- **H1**: effect of *seasonal change in the probability of larvae to pupate* (vs. entering in diapause),
  Probability to pupate decreases with temperature increase

- **H2**: effect of *a shorter period of inflorescence attractiveness*,
  with only the first phenological stages being attractive

- **H3**: a *seasonality effect*, that could reduce the number of females laying eggs at the end of the season ($F_{t,i} := \alpha F_{t,i}$ with $\alpha \in [0,1]$)
How can the rapid population decrease at the end of the season be explained?

- **H1/ temperature effect on the probability of larvae to pupate**: Estimated dynamics were not improved

- **H2/ effect of inflorescence attractiveness**:
  - Estimated dynamics were improved for solution-types 1 and 2, but only in plots S and H
How can the rapid population decrease at the end of the season be explained?

⇒ **H3/ seasonality effect**: 

- Estimated dynamics were improved in the three plots

  Low number of exogenous females and emergence of females in both L and H plots ($\mu_{\text{soil}_L}=0.94$ and $\mu_{\text{soil}_H}=0.92$)

- Two other solutions with lower ($\mu_{\text{soil}_H}=0.74$) or almost no ($\mu_{\text{soil}_H}=0.06$) emergence of females in plot H

  But estimated dynamics not as well improved in plot L
What about the effect of flowering synchronization on pest dynamics?

- Two flowering dynamics with the same number of inflorescences ($N = 7000$) but with 1 flush and 2 flushes were simulated.

**Budburst dynamics of the 7000 inflorescences**

- Flowering synchronization could reduce the number of pest:

<table>
<thead>
<tr>
<th>Model: Initial model +</th>
<th>Low weed cover</th>
<th>Synthetic mulching</th>
<th>High weed cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ attractiveness effect (solution-type 1)</td>
<td>-28%</td>
<td>-9%</td>
<td>-2%</td>
</tr>
<tr>
<td>+ seasonality effect (solution-type 1)</td>
<td>-39%</td>
<td>-14%</td>
<td>-37%</td>
</tr>
</tbody>
</table>
At this point:

- We identified a potential seasonality effect that can be modelled and quantified, but open questions on the biological processes involved
- We assessed the effects of management levers on pest dynamics

To go further in model-based design of management solutions, several developments are now considered:

- Accounting for pest-induced mortality of inflorescences to predict yield losses
- Accounting for multi-year effect of soil mulching treatment on the stock of larvae in diapause
- Coupling with V-Mango (Boudon et al. submitted), a functional-structural plant model predicting mango development and fruit growth
Thank you for your attention!

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Annex 1: emergence dynamic of larvae in diapause $f_D$

Number of adults emerging from larvae in diapause:

$$D_{t,i} = f_D(t)\text{ stock} \quad \text{with} \quad \sum_t f_D(t) = 1$$
Annex 2: Inflorescence dynamics for the first vs. all stages

All stages: C-D-E-F
First stages: C-D-E
Annex 3: What about the effect of flowering synchronization on pest dynamics?

Inflorescence dynamics for the first phenological stages (C-D-E) with 1 flush or 2 flushes.

Reduction in larvae number with flowering synchronization:

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<th>High weed cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ attractiveness effect (solution 1)</td>
<td>-28%</td>
<td>-9%</td>
<td>-2%</td>
</tr>
<tr>
<td>+ attractiveness effect (solution 2)</td>
<td>-74%</td>
<td>-71%</td>
<td>-66%</td>
</tr>
<tr>
<td>+ seasonality effect (solution 1)</td>
<td>-39%</td>
<td>-14%</td>
<td>-37%</td>
</tr>
<tr>
<td>+ seasonality effect (solution 2)</td>
<td>-53%</td>
<td>-22%</td>
<td>-34%</td>
</tr>
</tbody>
</table>
Annex 4: NSGA-II procedure

- Parent population $P_t$ of size $N$
  - Selection
  - Crossover
  - Mutation

- Offspring population $O_t$ of size $N$

- Population $R_t = P_t \cup O_t$ of size $2N$
  - Nondominated sorting

- Ranked nondominated fronts:
  - Front $F^1$ (nondominated solutions)
  - Front $F^2$ (solutions dominated only by $F^1$)
  - Front $F^i$ (solutions dominated only by $F^{i-1}$)

- NSGA-II procedure repeated 30 times [nsga2; Mersmann 2014]
- 6000 solutions
- Nondominated solutions [is_dominated; Mersmann 2012]