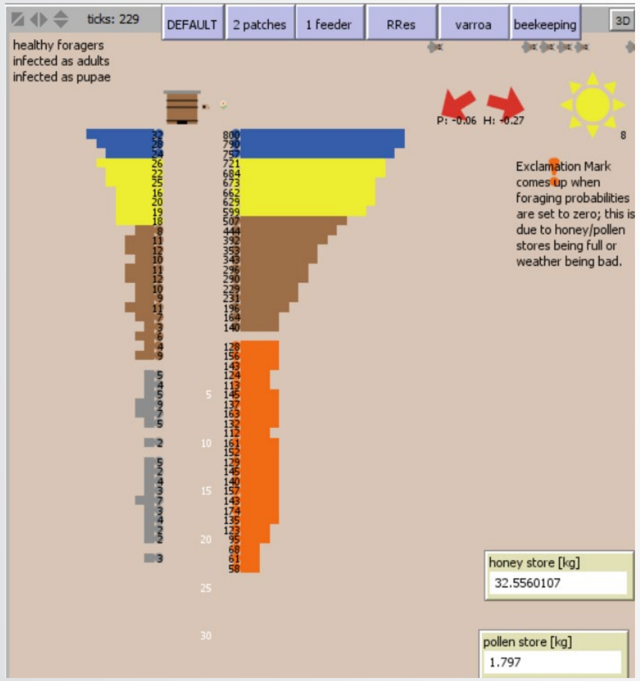
Getting BeeHave to Behave: Extending and Calibrating an Agent-Based Model of Honey Bee Dynamics for Pesticide Exposure Data Using Approximate Bayesian Computation (ABC)



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US Environmental Protection Agency

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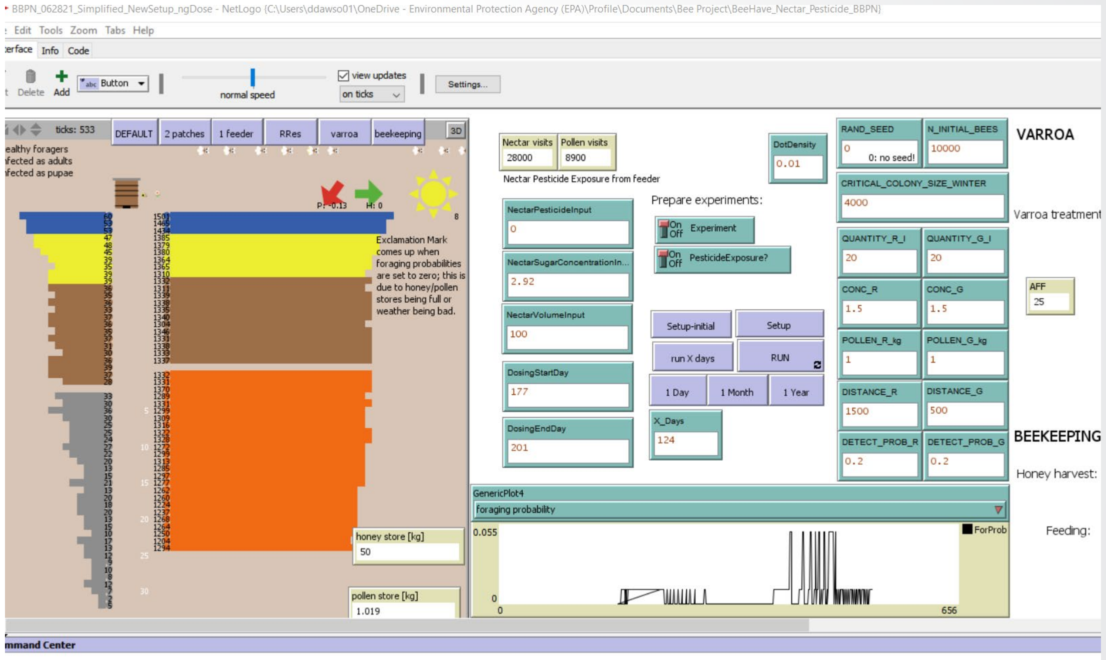
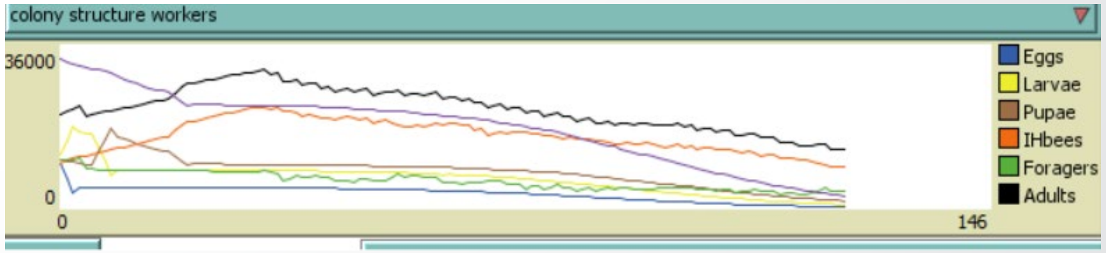
- The views expressed in this presentation are those of the authors and do not necessarily represent the views or the policies of the U.S. Environmental Protection Agency.

BeeHave

- Agent-based model of honey-bee colony dynamics
- Introduced by Becher et al. 2014
- Complex Model of Colony Structure
  - Stages
    - Energetics
    - Behavior
  - Ecological interactions
    - Weather
    - Daylight length
    - Landscape
    - Disease
  - Human management
- Multiple Interacting Agents
  - Life stage-based cohorts
  - Flowers/habitat patches





BeeHave

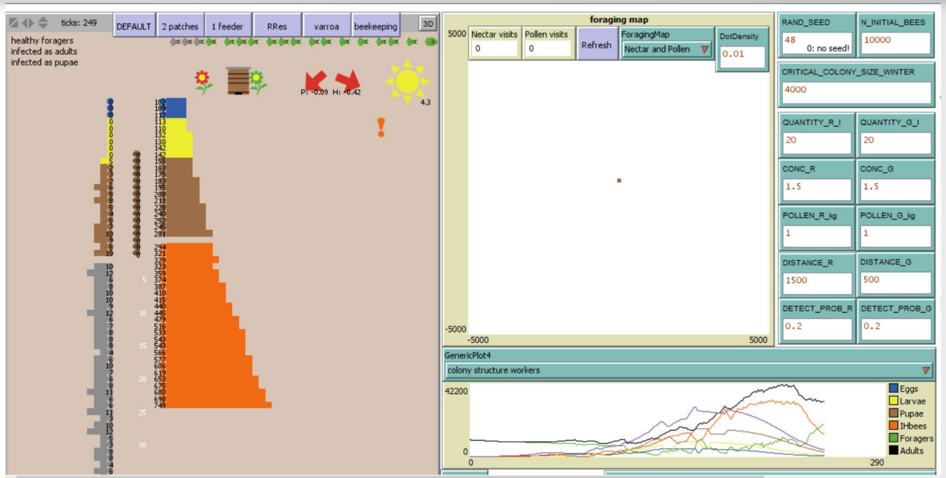
- Applications/Extensions of BeeHave
  - Colony collapse disorder
    - Evaluating management effects (Thorbek et al. 2017)
    - Role of parasites (Varroa mite) and viruses (Becher et al. 2014)
  - Pesticide exposure
    - Colony responses to changes in vital rates (Rumkee et al. 2015, Thorbek et al. 2017)
    - Colony responses to pesticide contamination of pollen (Schmolke et al. 2018)
  - BumbleBeeHave: related BeeHave model

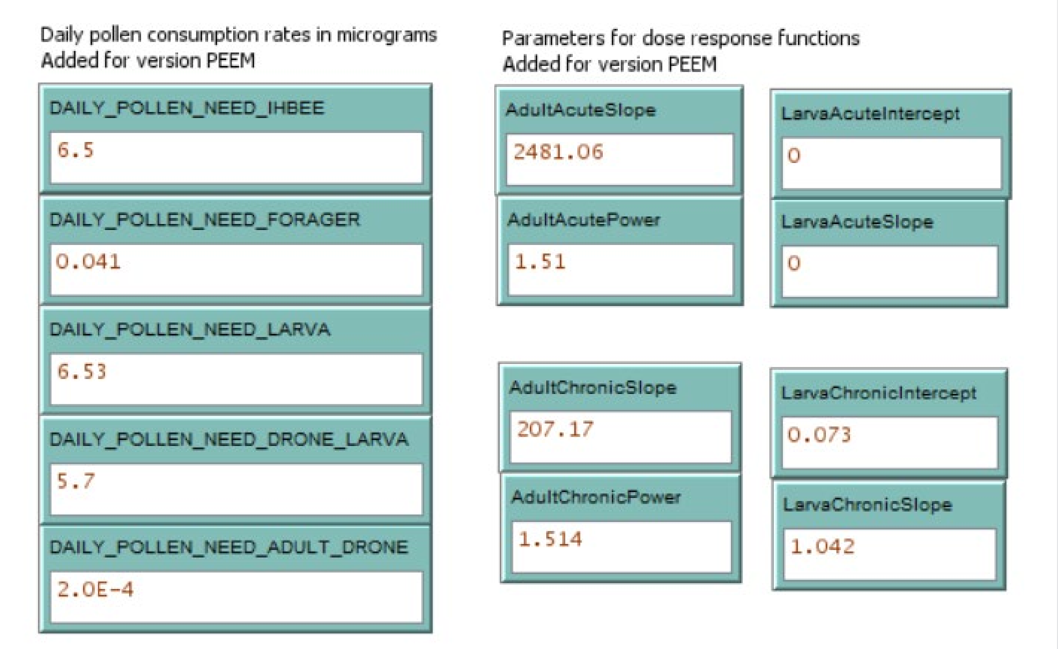
BeeHave: Application for Pesticide Risk Assessment

- Based on life history and considers important ecological interactions
- Exposure pathways can be modeled mechanistically
- Can be made spatially explicit: application to a variety of scenarios
  - Landscapes
  - Pesticides
- Open-source
  - Modifiable
  - Functions customizable/adaptable
  - Potentially calibratable to experimental data

Pesticide Exposure Module: Nectar

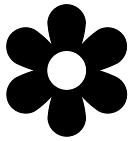
- Approach
  - Adapt BeeHave to include a pesticide exposure module: Nectar
    - Utilize mechanistic nectar collection module
      - Nectar collected from flowers, stored in hive
      - Collected nectar converted to energetics (kJ)
    - Exposure module
      - Base off of BeeHave_BeeMap_PEEM (BBP): Schmolke et al. 2018
        - Pollen-based exposure
        - Calculate mass of AI consumed
        - Dose-response model
  - Calibrate model to pesticide exposure data
    - Approximate Bayesian Computation
      - Likelihood Free Statistical Inference
      - Sequential Monte Carlo





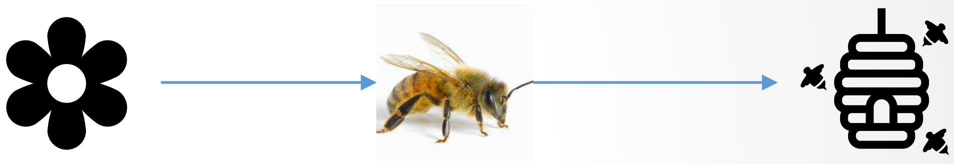
Modeling Nectar-based Exposure/Response to Pesticide

- Exposure pathway
  - Pesticide concentration is attributed to a nectar source



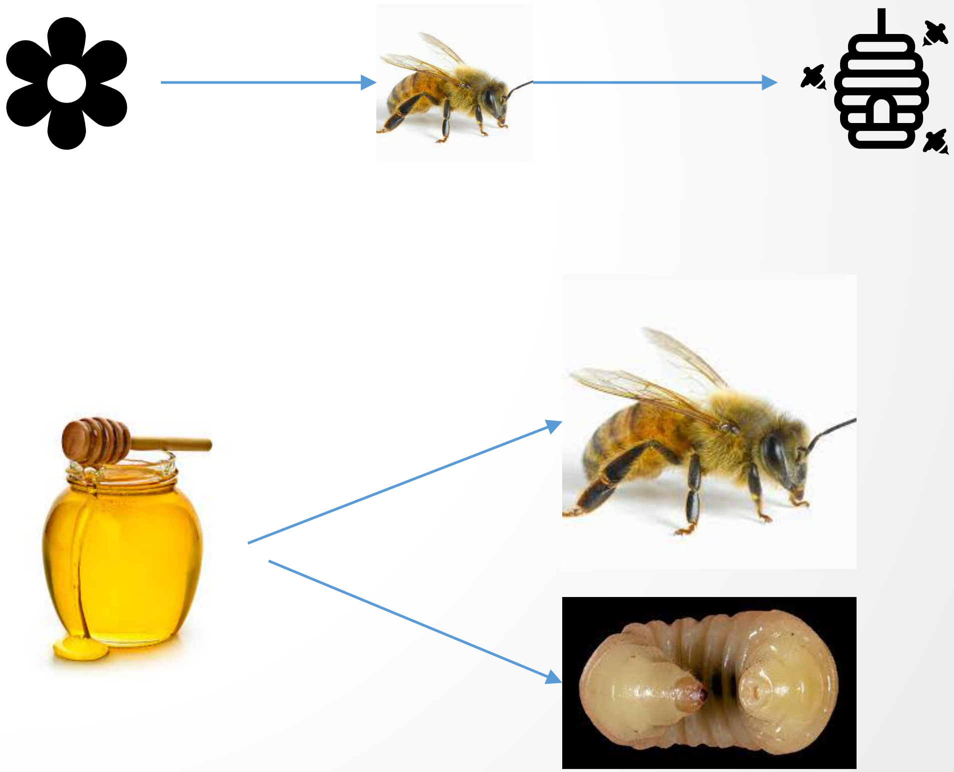
Modeling Nectar-based Exposure/Response to Pesticide

- Exposure pathway
  - Pesticide concentration is attributed to a nectar source
  - Foragers collect contaminated nectar and store it in the hive



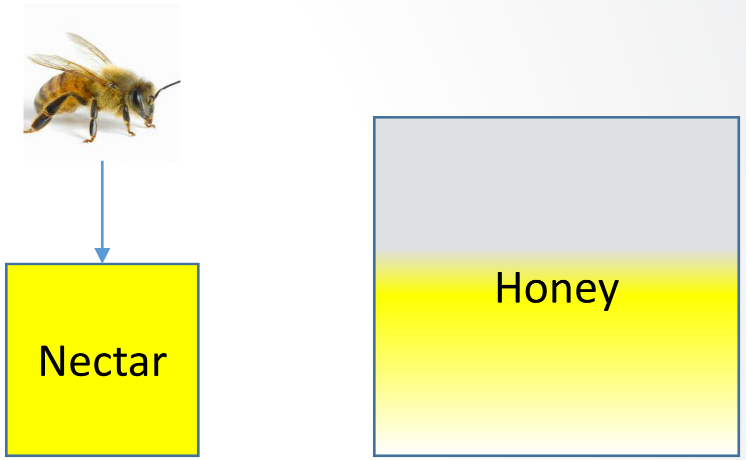
Modeling Nectar-based Exposure/Response to Pesticide

- Exposure pathway
  - Pesticide concentration is attributed to a nectar source
  - Foragers collect contaminated nectar and store it in the hive
  - Stages exposed to pesticide according to energetic needs



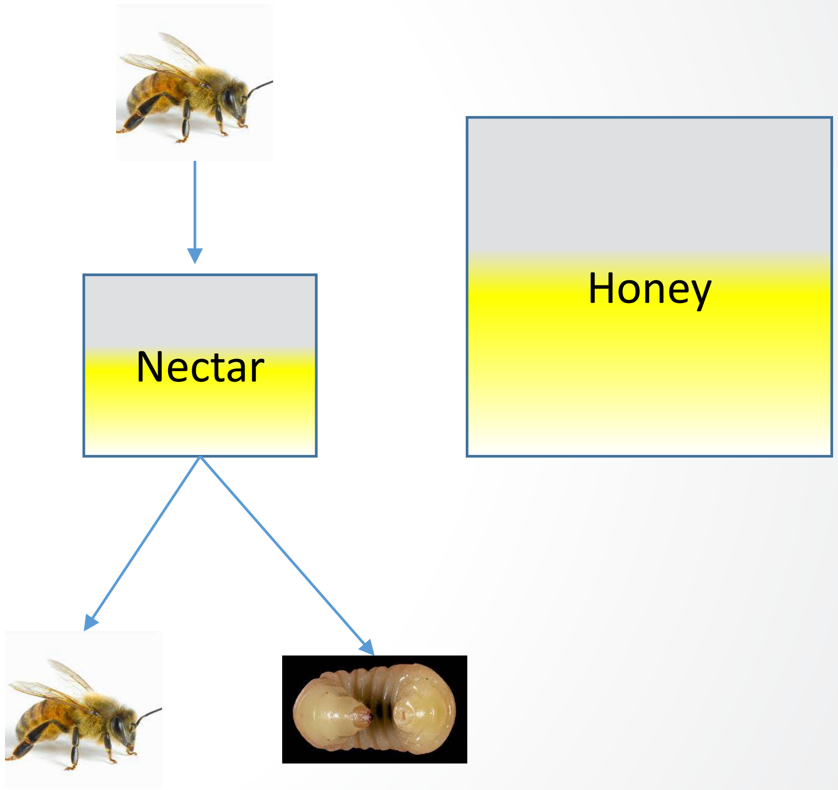
Nectar/honey dynamics

- Assume bees eat fresh nectar if available
- Consume stored honey otherwise
- Daily nectar goes into nectar tank



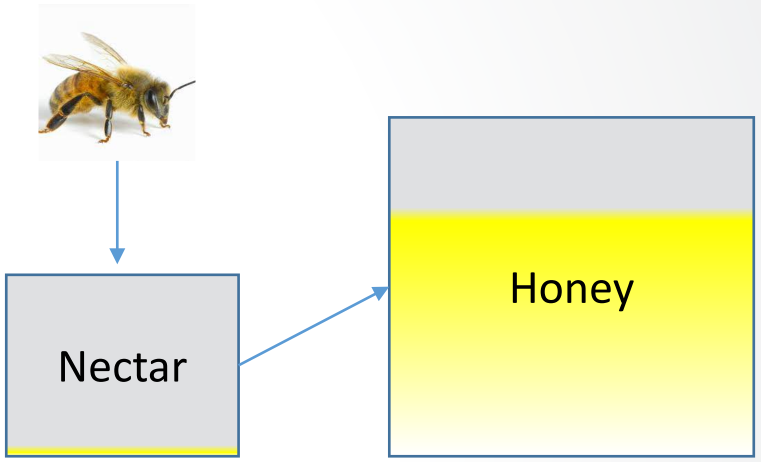
Nectar/honey dynamics

- Assume bees eat fresh nectar if available
- Consume stored honey otherwise
- Daily nectar goes into nectar tank
- Daily energy needs are met from nectar tank.
  - If no nectar is available, honey is used.



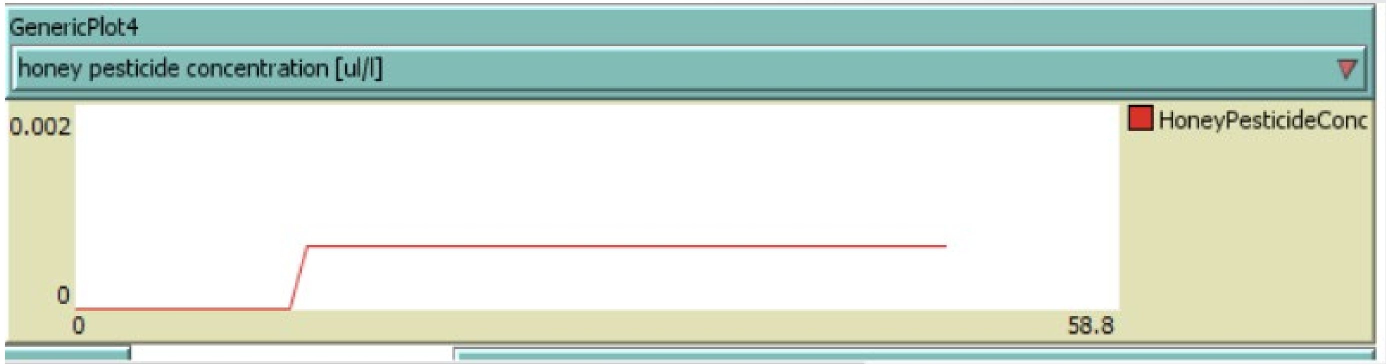
Nectar/honey dynamics

- Assume bees eat fresh nectar if available
- Consume stored honey otherwise
- Daily nectar goes into nectar tank
- Daily energy needs are met from nectar tank.
  - If no nectar is available, honey is used.
- Remaining nectar into honey tank
- If no nectar is available, honey is used.



Exposure Accounting

- Pesticide concentration tracked in µg AI/kJ of energy
- Pesticide concentration in nectar tank added to honey tank concentration.
    - Perfect, complete, and instant mixing is assumed
- Stage-cohort total consumption of AI per day tracked
    - Larvae
    - Adults
        - Drones
        - In Hive Bees
        - Foragers



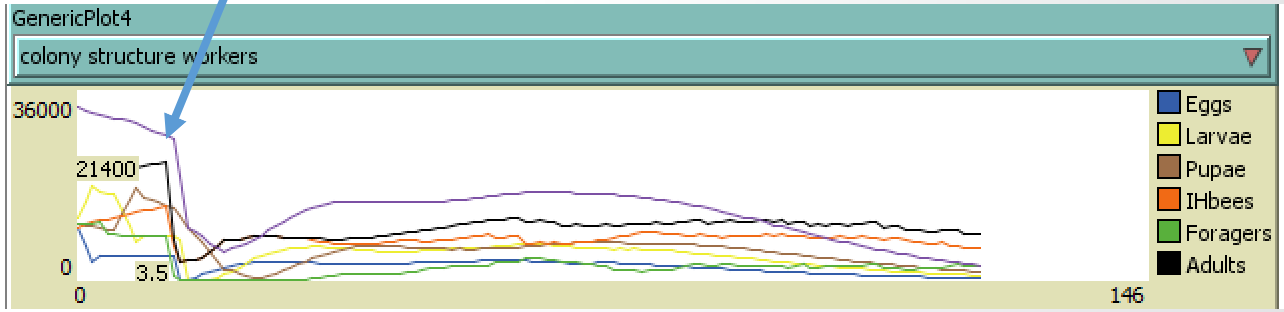
Model Calibration

- Colony Feeding Study
  - Conducted in North Carolina with clothianidin
  - Contaminated nectar placed in feeder next to hives in each test case
    - 6 concentrations (0, 10,20,40,80, 160 ppb)
  - 12 sites
    - 2 reps per site for 0 ppb
    - 1 rep per site for other concentrations
  - Contaminated nectar made available for ≈ 3 weeks starting in June (177)
  - Trials continue through October
  - Numbers of adult and eggs estimated at 4 times

Experimental Simulation

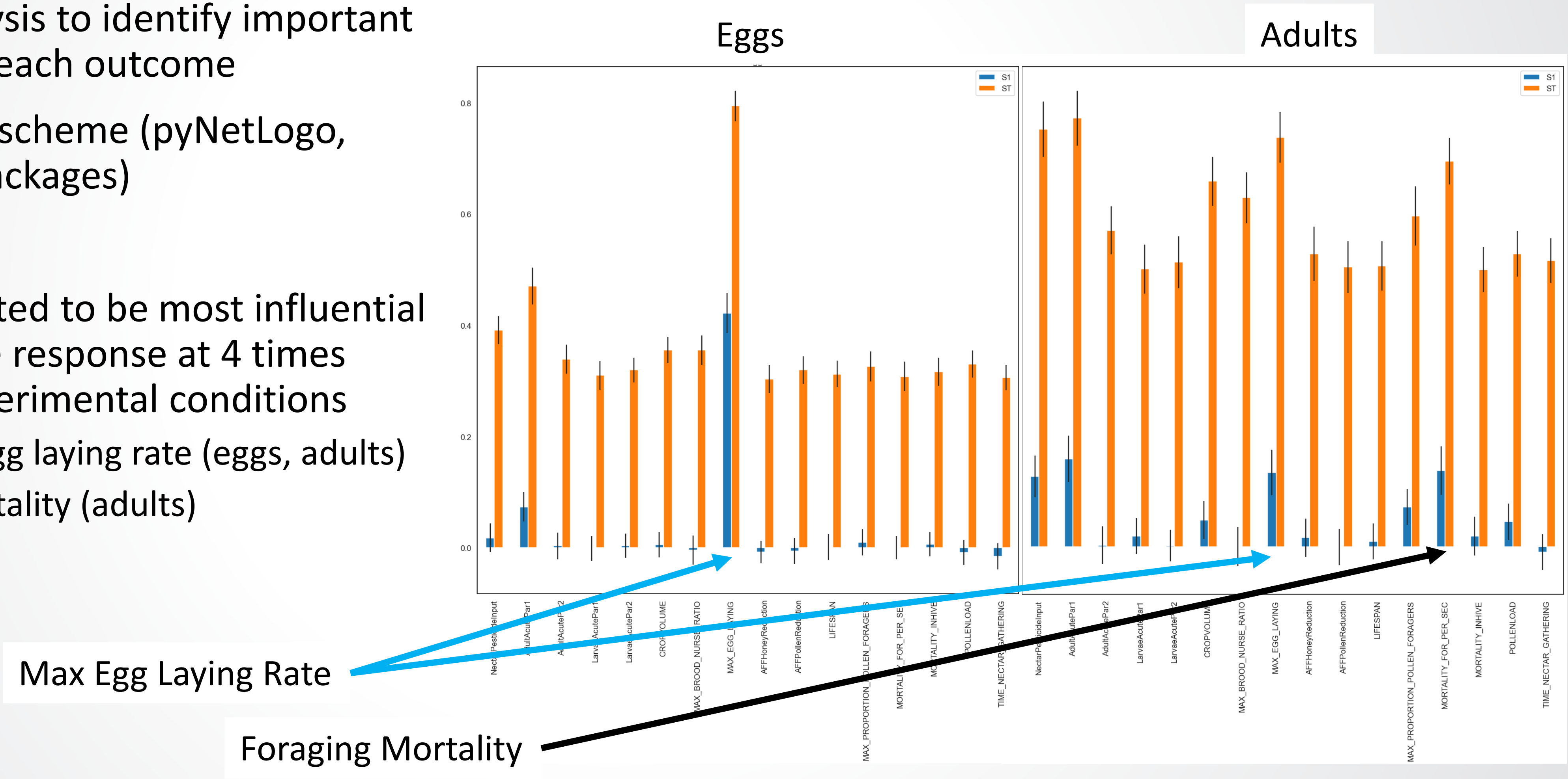
- Experiment scenario developed for model
  - Single hive
  - Pesticide feeder patch placed close to hive
  - Generalized landscape patch: 500 m
    - Unlimited nectar
    - Unlimited pollen
  - Initial conditions
    - Numbers of each stage sampled from distribution
  - Schedule
    - Start day: 168 (June 17)
    - Start feeding day: 177
    - Stop feeding day: 201
    - Stop day: 292 (October 19th)
  - 6 concentrations
  - Outputs per timestep
    - Numbers of Eggs
    - Numbers of Adults (Foragers + In Hive bees)

Feeding Start



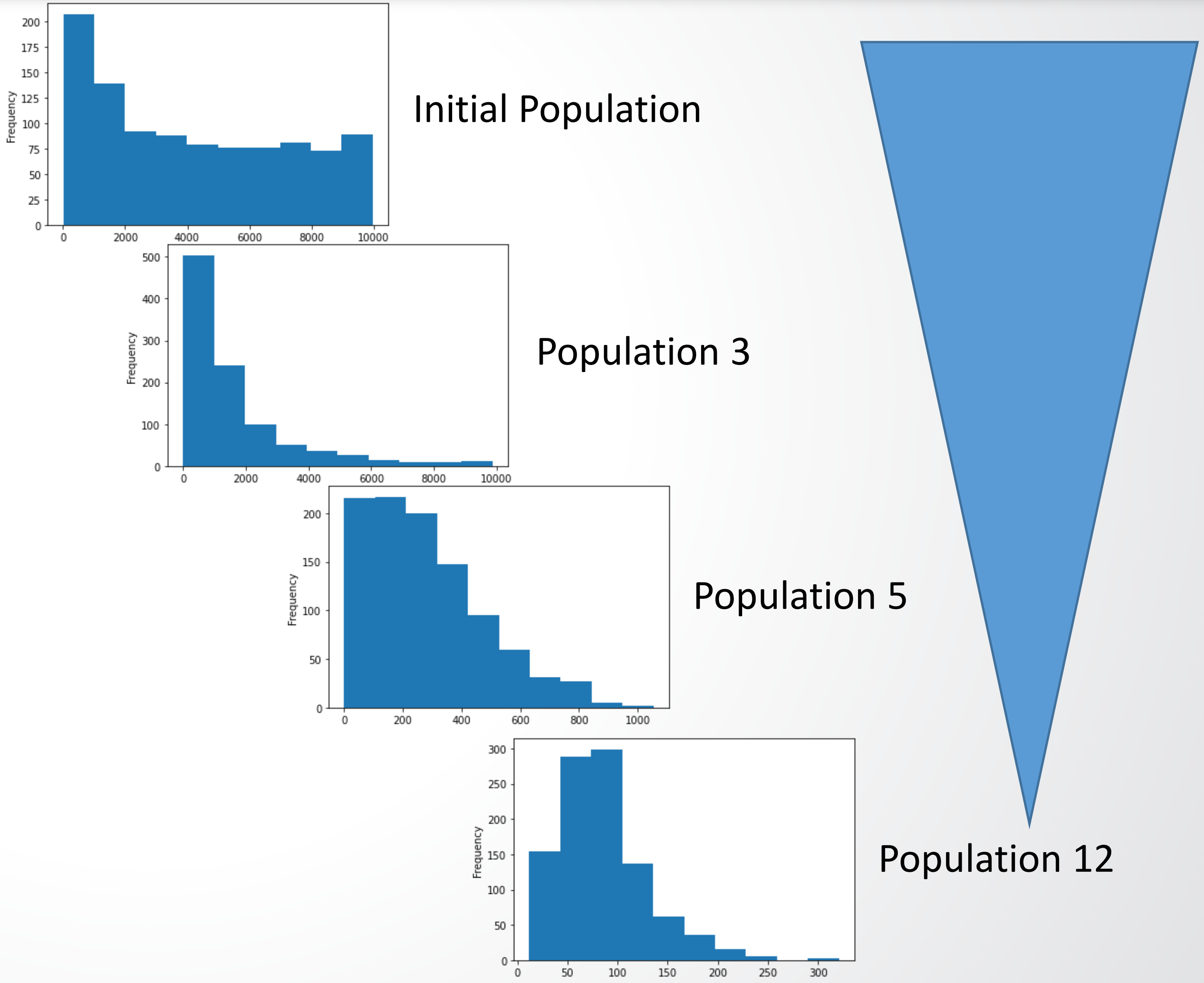
Model Calibration

- Sensitivity analysis to identify important parameters for each outcome
- Sobol sampling scheme (pyNetLogo, sobol python packages)
- 16 parameters
- Two demonstrated to be most influential other than dose response at 4 times throughout experimental conditions
  - Maximum egg laying rate (eggs, adults)
  - Forager mortality (adults)

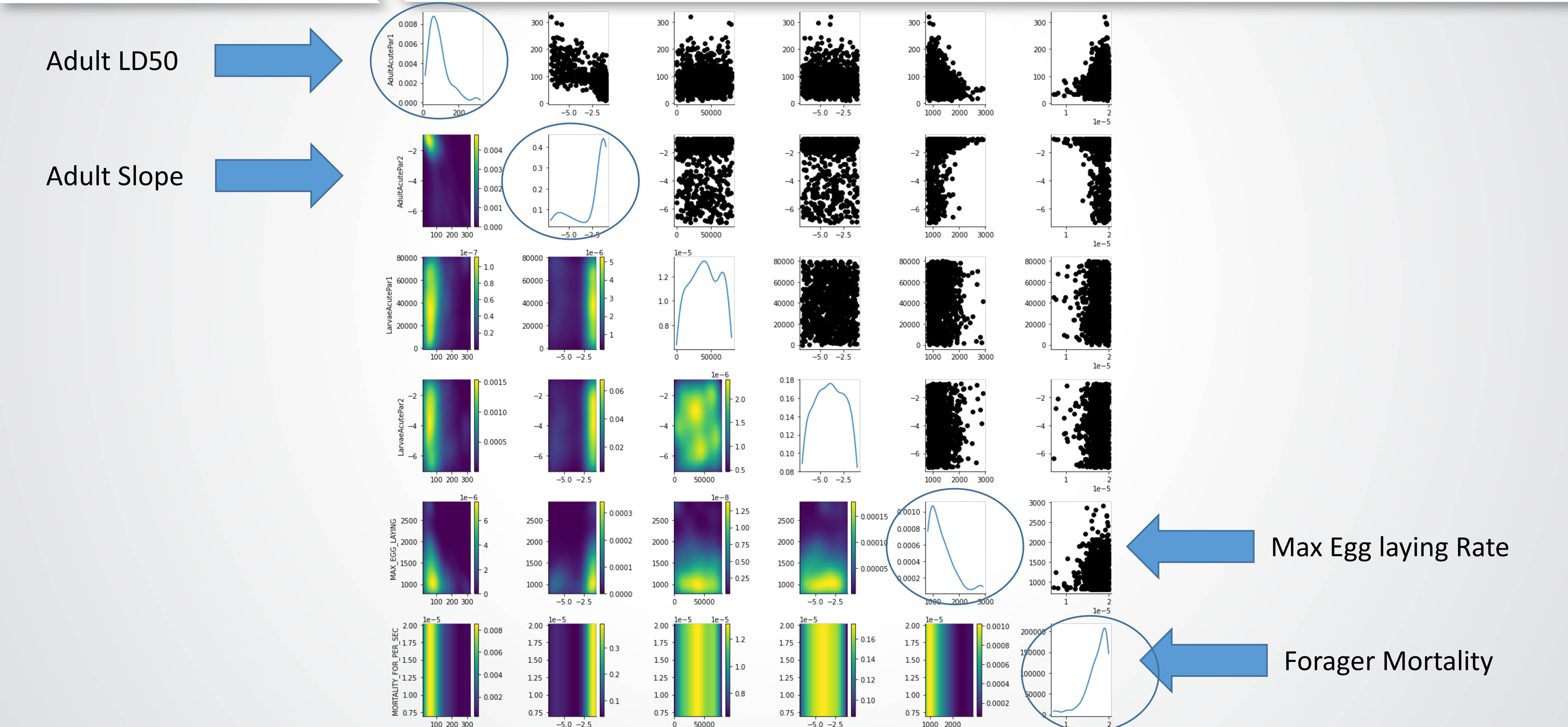


Model Calibration

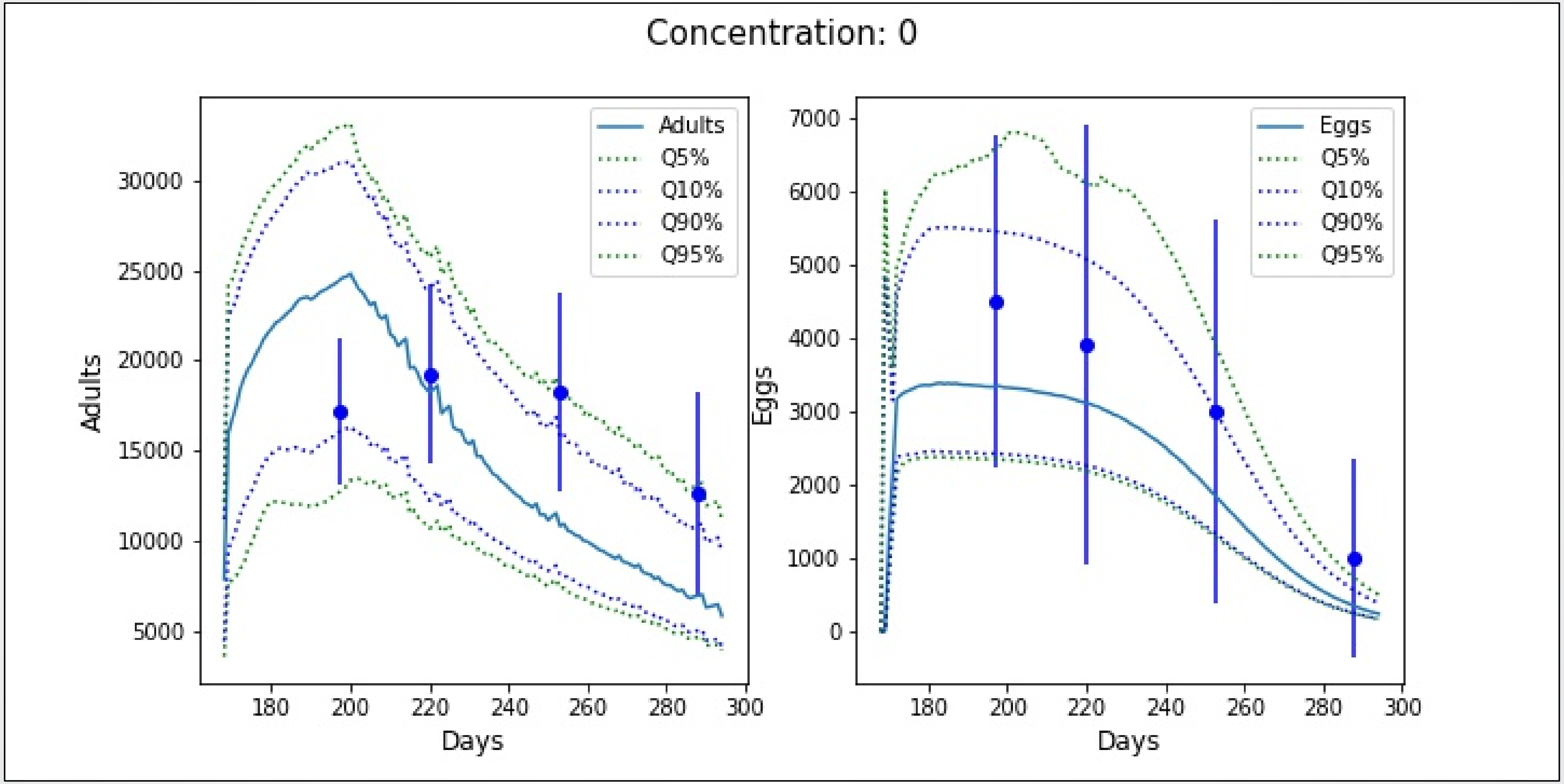
- ABC calibration using pyNetLogo & pyABC
  - 6 parameters to be calibrated
  - Outputs assessed against field data at 4 times
  - Parameter distribution estimation: Sequential Monte Carlo simulation
    - 1000 “particles” per population
    - As number of populations increase
      - Posterior distributions of parameters gets closer to true posteriors
      - Acceptance rate typically goes down
      - Computational cost increases
  - 12 populations sequentially assembled



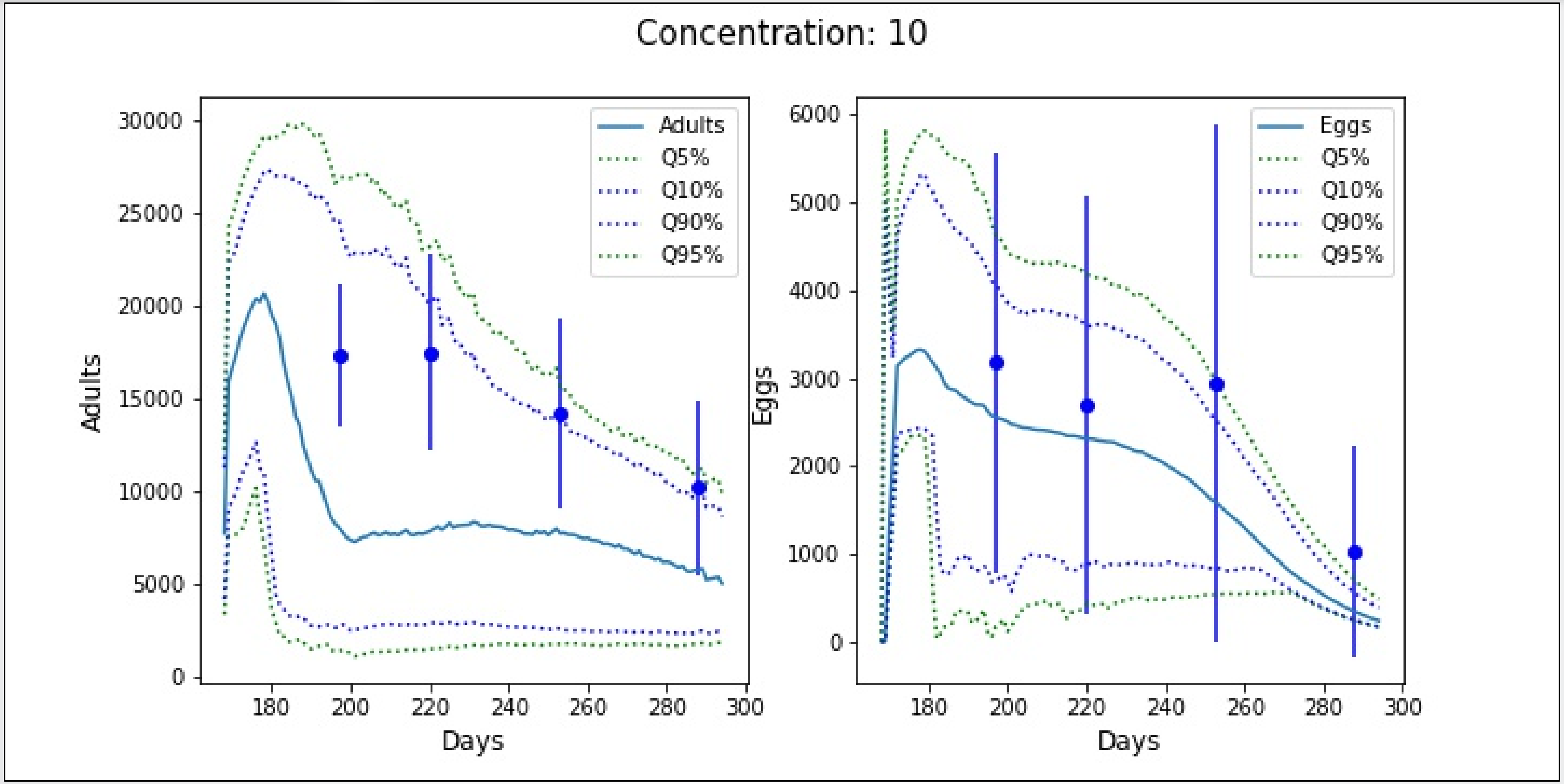
Marginal Parameter Distributions



Forward Predictions: 0 ppb

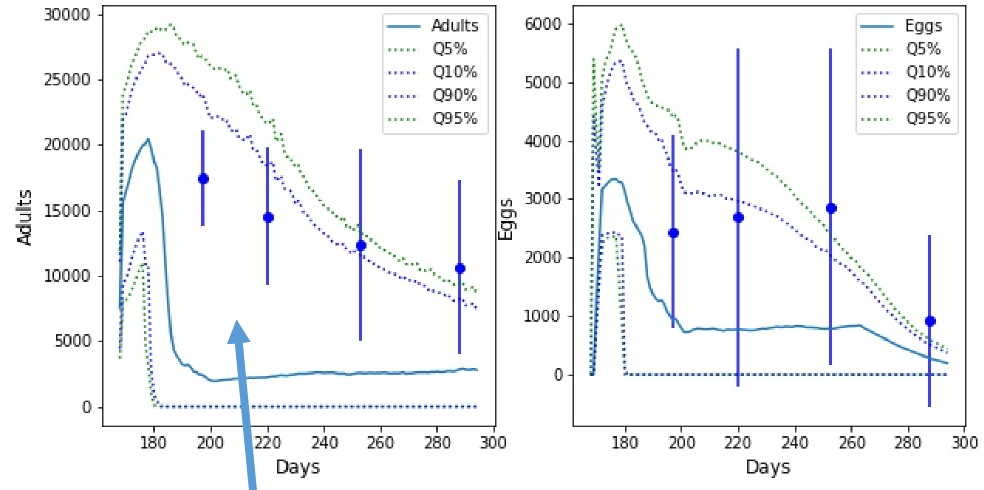


Forward Predictions: 10 ppb

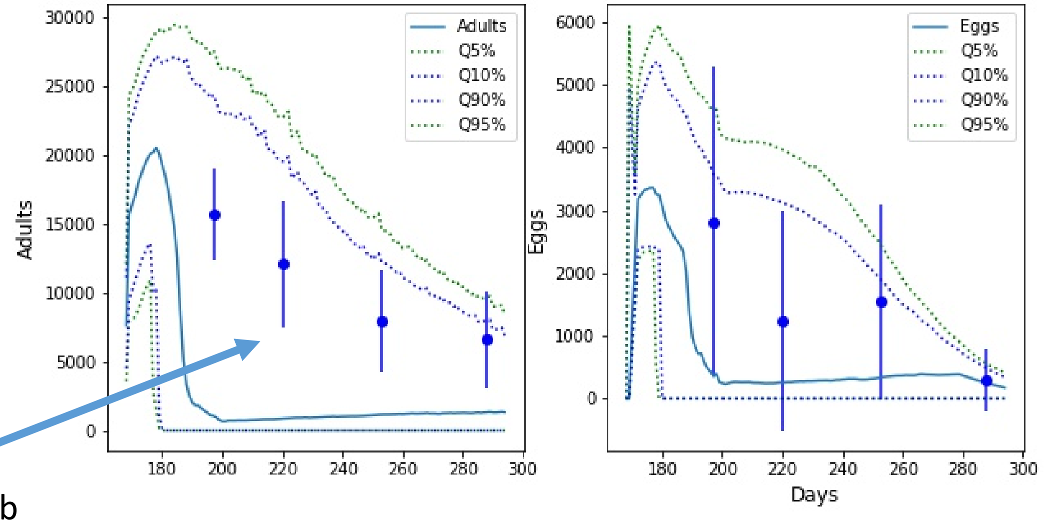


Forward Predictions: 40-160

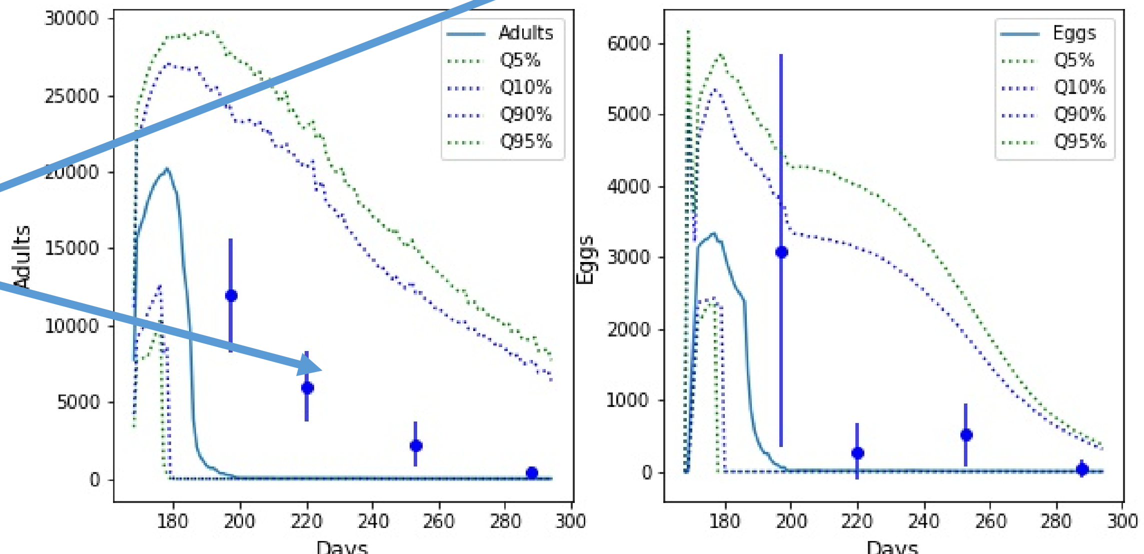
Concentration: 40 ppb



Concentration: 80 ppb



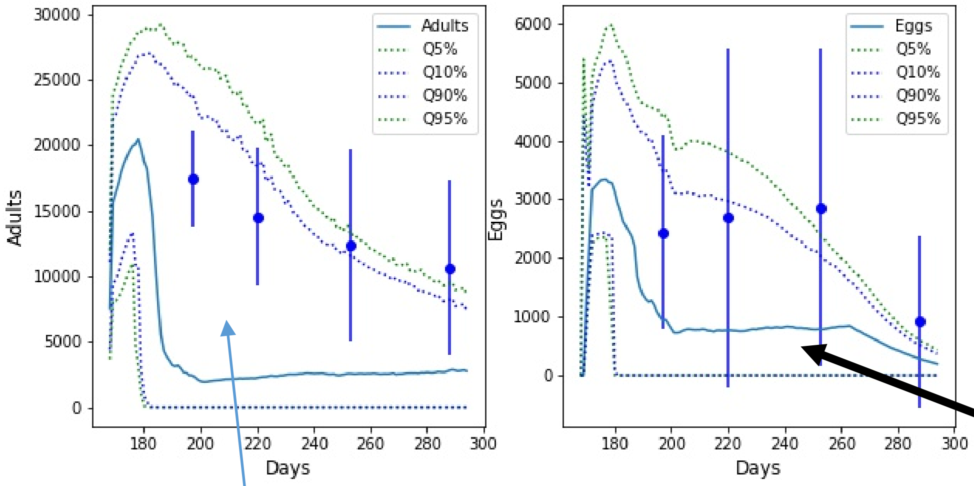
Concentration: 160 ppb



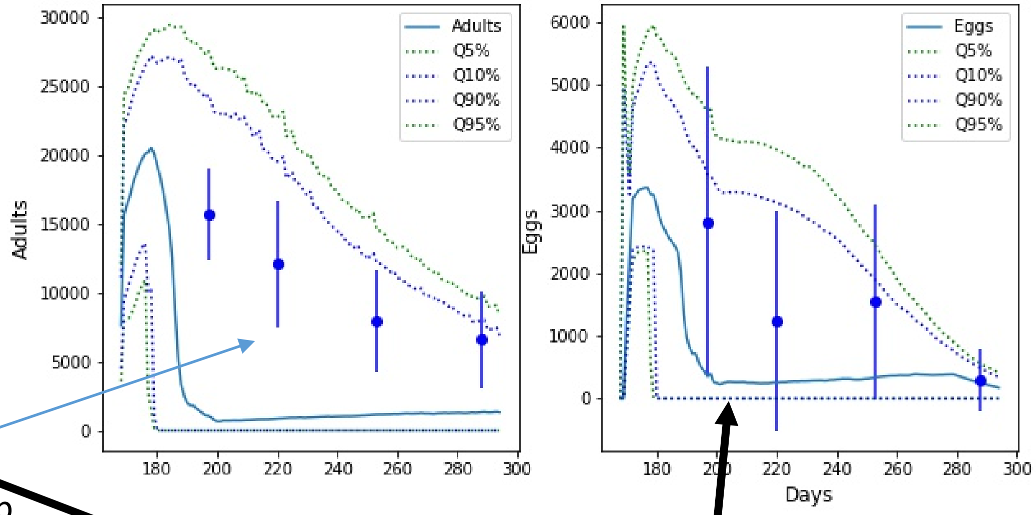
Adults drastically under predicted as concentration increases

Forward Predictions: 40-160 ppb

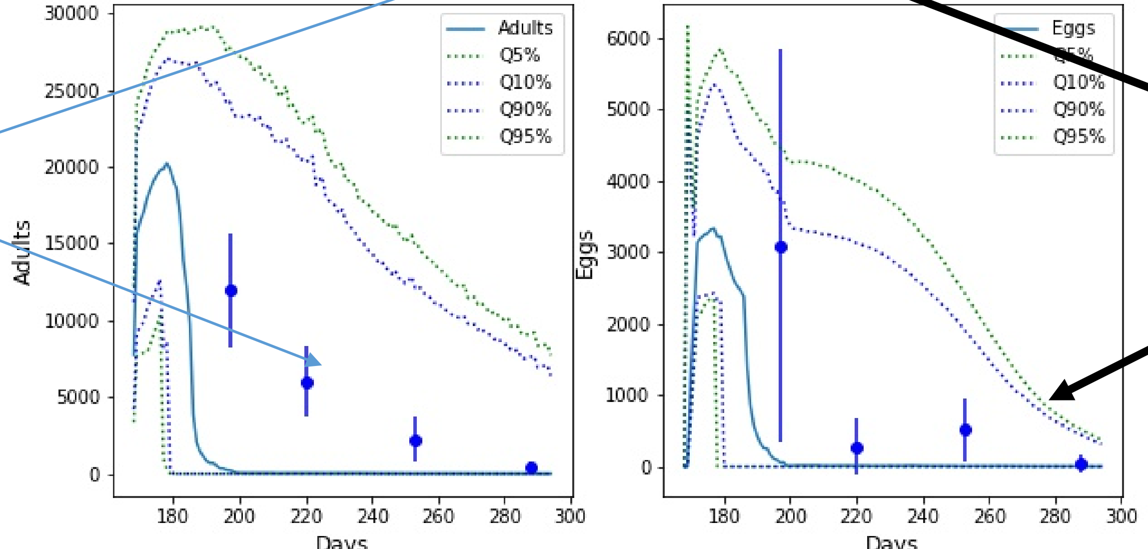
Concentration: 40 ppb



Concentration: 80 ppb



Concentration: 160 ppb



Adults drastically under predicted

Modeled egg mean is under predicted overlaps with collected data

Results & Next Steps

- ABC calibration reasonably reproducing range of egg population responses
- Underpredicting adults
  - Effect of seasonal decline too strong
  - Overly sensitive to pesticide
- Next steps
  - Continue calibration, focusing on influential parameters for adults
    - LC50
    - Foraging mortality
  - Consider landscape effects
  - Compare with BeePop+, another model of colony dynamics calibrated against the field dataset
    - Structure
    - Calibrated dose response parameter values

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Thanks! Questions?

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