Supporting Information

Predicting honeybee colony failure: using the BEEHAVE model to simulate colony responses to pesticides

Authors: Jack C. O. Rumkee †; Matthias A. Becher †; Pernille Thorbek ‡; Peter J. Kennedy †;
Juliet L. Osborne *†

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Appendix 1

Table S1

Characteristics of specific life stages used in the BEEHAVE model relating to life stage duration, food requirement and major source of mortality. Values are parameters set in the model (Becher et al. 2014)

* In-hive bees will become foragers after between 7 and 50 days depending on colony conditions

† Nectar consumption increases with level of brood care

| Life-stage      | Time spent in stage | Honey Requirement (mg/day) | Pollen Requirement (mg/day) | Major source of mortality        |
|-----------------|---------------------|----------------------------|-----------------------------|----------------------------------|
| Egg             | 3 days              | 0                          | 0                           | Lack of care                     |
| Larva           | 6 days              | 10.9                       | 23.6                        | Lack of food/care                |
| Pupa            | 12 days             | 10.9                       | 23.6                        | Lack of care                     |
| In-Hive Worker  | Variable* (mean 17 days) | 11(53.42)†             | 1.5                         | Background mortality             |
| Forager         | Until death (Summer average 24.5 days Winter average 143 days) | 11 + for foraging | 1.5                         | Foraging mortality               |
Table S2

Percentage of the 30 replicate colonies surviving 3 years of an imposed stress of a set percent mortality on one life stage for one month of the year. A colony that has more than 4000 bees at the end of three years is assumed to survive the winter.

|                | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **Set Percent**|     |     |     |     |     |     |     |     |     |     |     |     |
| **Daily Larval Mortality** |     |     |     |     |     |     |     |     |     |     |     |     |
| 1%             | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 5%             | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 10%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 25%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 50%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| **Daily In-Hive Mortality** |     |     |     |     |     |     |     |     |     |     |     |     |
| 1%             | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 5%             | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 10%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 25%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 50%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| **Daily Forager Mortality** |     |     |     |     |     |     |     |     |     |     |     |     |
| 1%             | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 5%             | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 10%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 25%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 50%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| **Per-Trip Forager Mortality** |     |     |     |     |     |     |     |     |     |     |     |     |
| 1%             | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 2.5%           | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 5%             | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 7.5%           | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 10%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| **Combined Mortality** |     |     |     |     |     |     |     |     |     |     |     |     |
| 1%             | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 5%             | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 10%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 25%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
| 50%            | 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%| 100%|
**Figure S1  Reducing egg-laying rate**

The mean number of bees alive in a colony (± standard error) at the end of three year simulations (n = 30) when the colony is subject to a reduction in the egg-Laying rate (ELR) for one month in the year.
**Figure S2 Increasing mortality as a multiple of control**

The number of bees alive in the colony (± standard error) at the end of three year simulations (n = 30) when the colony is subject increased mortality, (multiple of the model control mortality) of certain life stages for one month in the year. The standard error of the mean is shown.

A: Larval daily mortality

B: In-Hive worker mortality

C: Forager daily mortality

D: Forager per trip mortality.
Figure S3 Increasing mortality by a set percentage

The number of bees alive in the colony (± standard error) at the end of three year simulations (n = 30) when the colony is subject increased mortality (set percentage mortality) of certain life stages for one month in the year. The standard error of the mean is shown.

A: Larval daily mortality
B: In-Hive worker daily mortality
C: Forager daily mortality
D: Forager per trip mortality
Figure S4 Increasing mortalities of three life stages by multiple of control and by a set percentage

The number of bees alive in the colony (± standard error) at the end of three year simulations (n = 30) when the colony is subject increased mortality (set percentage mortality), of larvae, in-hive workers and foragers for one month in the year. The standard error of the mean is shown.
**Figure S5**

Detailed effects of imposing 25% daily larval mortality in June. Black solid line represents the control scenario and the red dashed line represents the treatment scenario. The treatment period is between the vertical lines. Data was collected from BEEHAVE simulations set up exactly as described in the methods, taking values at the end of each day in the model.

A: Number of workers in colony

B: Number of larvae in colony

C: Number of larval deaths from lack of food or brood care
**Figure S6**

Detailed effects of imposing 5% daily in-hive worker mortality in June. Black solid line represents the control scenario and the red dashed line represents the treatment scenario. The treatment period is between the vertical lines. Data was collected from BEEHAVE simulations set up exactly as described in the methods, taking values at the end of each day in the model.

A: Number of workers in colony;  B: Number of larvae in colony;  C: Number of larval deaths from lack of food or brood care;  D: Age when workers first become foragers (days);  E: Honey store of the colony (J);  F: Pollen stores in the colony (g)
Figure S7

The increase in in-hive worker deaths in the colony after the addition of an extra 5% daily in-hive worker mortality in a month compared to the control. The points show the increase in number of in-hive worker deaths each day during the treatment month compared to the same month in a control simulation. The values below each month give the total difference in in-hive worker deaths for the month in question.

| Month | Increased in-hive worker deaths | Difference in total deaths over month |
|-------|---------------------------------|--------------------------------------|
| Jan   | 12                              | 12                                   |
| Feb   | 397                             | 397                                  |
| Mar   | 776                             | 776                                  |
| Apr   | 2812                            | 2812                                 |
| May   | 11421                           | 11421                                |
| Jun   | 18314                           | 18314                                |
| Jul   | 26092                           | 26092                                |
| Aug   | 40416                           | 40416                                |
| Sep   | 17308                           | 17308                                |
| Oct   | 2145                            | 2145                                 |
| Nov   | 277                             | 277                                  |
| Dec   | 77                              | 77                                   |
Appendix 2.

Changes to BEEHAVE model that were used in all simulations in this study

The BEEHAVE model can be downloaded at [www.beehave-model.net](http://www.beehave-model.net). Included in the download are a manual and ODD (Overview, Design concepts and Details) document describing the model and how to operate it in more detail.

Changes to the interface tab

Added “Inputs” for new global variables:

- Treatment_Day – Day in which treatment period begins
- Treatment_Period – Length (in days) of treatment period
- EggLayingReduction - % reduction of ELRt during treatment period
- LarvalMortalityIncrease – multiple of default larval background mortality during treatment period
- LarvalMortalityPercent - % larval mortality during treatment period
- InHiveMortalityIncrease – multiple of default in-hive worker background mortality during treatment period
- InHiveMortalityPercent - % in-hive worker mortality during treatment period
- ForagerMortalityIncrease – multiple of default forager mortality during treatment period
- ForagerMortalityPercent - % forager mortality during treatment period

Added “Switches” to turn stress effects on and off

- ReducedEggLaying – Daily ELRt will be reduced during treatment period
- LarvalMortality – Daily larval mortality will be increased during treatment period
- InHiveMortality – Daily in-hive mortality will be increased during treatment period
- ForagerMortalityPerDay – Daily forager mortality will be increased during treatment period
- ForagerMortalityPerTrip – Per Trip forager mortality will be increased during treatment period
Added “Chooser” to select how mortality effect will be applied

PesticideMortalityType

Options:

“Multiple” – mortality is applied as a multiple of the default mortality

“Set Percent” – mortality is applied as a defined percent.

**Changes and Additions to the code tab**

Reducing egg-laying rate starting on the treatment day lasting for the treatment period

In ‘NewEggsProc’

Before line:

```
Set NewWorkerEggs round ELRt ; ROUND ! in contrast to HoPoMo
```

Added:

```
if (ReducedEggLaying = True)
[
  if ((day >= Treatment_Day) and (day < (Treatment_Day + Treatment_Period)))
    set ELRt ELRt * EggLayingReduction
]
```

Altering larval mortality, either by multiplying the control mortality or by setting the mortality to a defined percent.

In ‘WorkerLarvaeDevProc’

Replaced line:
set numberDied random-poission (number * MORTALITY_LARVAE)

with:

ifelse(LarvalMortality = true)
  
  ifelse ((day >= Treatment_Day) and (day < Treatment_Day + Treatment_Period))
    
    if (PesticideMortalityType = "Multiple")
      
      set numberDied random-poission (number * MORTALITY_LARVAE) * LarvalMortalityIncrease
    
    if (PesticideMortalityType = "Set Percent")
      
      set numberDied (number * LarvalMortalityPercent)
    
  
  set numberDied random-poission (number * MORTALITY_LARVAE)

Alterating in-hive worker mortality, either by multiplying the control mortality or by setting the mortality to a defined percent.

In WorkerIHbeesDevProc

Replace Line:

set desthsCounter random-poission (number_healthy * MORTALITY_INHIVE)

With:
ifelse (InHiveMortality = true)
  [ ifelse (day >= Treatment_Day and day < (Treatment_Day + Treatment_Period))
    [ if (PesticideMortalityType = "Multiple")
      [ set deathsCounter random-poission (number_healthy * MORTALITY_INHIVE * InHiveMortalityIncrease) ]
    ]
  ]
  [ if (PesticideMortalityType = "Set Percent")
    [ if( day >= Treatment_Day and day < (Treatment_Day + Treatment_Period))
      [ set deathsCounter (number_healthy * InHiveMortalityPercent) ]
    ]
  ]
  [ set deathsCounter random-poission (number_healthy * MORTALITY_INHIVE) ]
]

Replace line:
set deathsCounter random-poission (number_infectedAsPupa * MORTALITY_INHIVE_INFECTED_AS_PUPA)

With:

ifelse (InHiveMortality = true)
  [ ifelse (day >= Treatment_Day and day < (Treatment_Day + Treatment_Period))
    [ if (PesticideMortalityType = "Multiple")

[ set deathsCounter random-poisson (number_infectedAsPupa * MORTALITY_INHIVE_INFECTED_AS_PUPA * InHiveMortalityIncrease) ]

if (PesticideMortalityType = "Set Percent")
[ set deathsCounter (number_infectedAsPupa * InHiveMortalityPercent) ]
]
]

set deathsCounter
random-poisson (number_infectedAsPupa * MORTALITY_INHIVE_INFECTED_AS_PUPA)
]
]
[ set deathsCounter
random-poisson (number_infectedAsPupa * MORTALITY_INHIVE_INFECTED_AS_PUPA)
]

Replace line:

set deathsCounter random-poisson (number_infectedAsAdult * MORTALITY_INHIVE_INFECTED_AS_ADULT)

With:

ifelse (InHiveMortality = true)
[ ifelse ( day >= Treatment_Day and day < (Treatment_Day + Treatment_Period))
[ if (PesticideMortalityType = "Multiple")
[}
Altering the mortality applied to foragers at the flower patch, either by multiplying the control mortality or by setting the mortality to a defined percent.

In ‘FlowerPatchesUpdateProc’

At end of procedure, add:

```plaintext
if (ForagerMortalityPerTrip = True)
  [  
    if (PesticideMortalityType = "Multiple")
      [  
        if ((day >= Treatment_Day) and (day < (Treatment_Day + Treatment_Period)))
          [  
            set mortalityRisk (mortalityRisk * ForagerMortalityIncrease)
            set mortalityRiskPollen (mortalityRiskPollen * ForagerMortalityIncrease)
          ]
      ]
  ]
```

```
if (PesticideMortalityType = "Set Percent")
```
Altering forager mortality, either by multiplying the control mortality or by setting the mortality to a defined percent.

In ‘ForagersLifespanProc’

Replace:

let dailyRiskToDie MORTALITY_INHIVE
    ; the daily background mortality of (healthy) foragers, which is equal to MORTALITY_INHIVE of the inhive bees

    if infectionState = "infectedAsPupa"
        set dailyRiskToDie MORTALITY_INHIVE_INFECTED_AS_PUPA
    ] ; except for infected as pupa foragers, which have a higher mortality

    if infectionState = "infectedAsAdult"
        set dailyRiskToDie MORTALITY_INHIVE_INFECTED_AS_ADULT
    ] ; except for infected as adult foragers, which have a higher mortality
With:

    set dailyRiskToDie MORTALITY_INHIVE
    ; the daily background mortality of (healthy) foragers, which is equal to MORTALITY_INHIVE of the inhive bees

    ;Added by JRumkee
    if (ForagerMortalityPerDay = True)
        if (PesticideMortalityType = "Multiple")
            if ((day >= Treatment_Day) and (day < (Treatment_Day + Treatment_Period)))
\[
\text{set dailyRiskToDie (MORTALITY\_INHIVE \ast \text{ForagerMortalityIncrease})}
\]

\]

\text{if (PesticideMortalityType = "Set Percent")}
\[
\text{if ((day} \geq \text{Treatment\_Day}) \text{and (day} < \text{(Treatment\_Day} \text{+ Treatment\_Period))))}
\[
\text{set dailyRiskToDie (ForagerMortalityPercent)}
\]
\]
\]
\]
\]
\]

\text{if infectionState = "infectedAsPupa"}
\[
\text{set dailyRiskToDie MORTALITY\_INHIVE\_INFECTED\_AS\_PUPA}
\]
\]
\]
\]
\]

; except for infected as pupa foragers, which have a higher mortality
\]
\]
\]
\]
\]

; Added by JRumkee
\]
\]
\]
\]
\]

\text{if (ForagerMortalityPerDay = True)}
\[
\text{if (PesticideMortalityType = "Multiple")}
\[
\text{if ((day} \geq \text{Treatment\_Day}) \text{and (day} < \text{(Treatment\_Day} \text{+ Treatment\_Period))))}
\[
\text{set dailyRiskToDie (MORTALITY\_INHIVE\_INFECTED\_AS\_PUPA \ast \text{ForagerMortalityIncrease})}
\]
\]
\]

\text{if (PesticideMortalityType = "Set Percent")}
\[  

if ((day >= Treatment_Day) and (day < (Treatment_Day + Treatment_Period)))
[
    set dailyRiskToDie (ForagerMortalityPercent)
]

; End

if infectionState = "infectedAsAdult"
[
    set dailyRiskToDie MORTALITY_INHIVE_INFECTED_AS_ADULT
    ; except for infected as adult foragers, which have a higher mortality

    ; Added by JRumkee
    if (ForagerMortalityPerDay = True)
    [
        if (PesticideMortalityType = "Multiple")
        [
            if ((day >= Treatment_Day) and (day < (Treatment_Day + Treatment_Period)))
            [
                set dailyRiskToDie (MORTALITY_INHIVE_INFECTED_AS_ADULT * ForagerMortalityIncrease)
            ]
        ]
    ]

    if (PesticideMortalityType = "Set Percent")
    [
        if ((day >= Treatment_Day) and (day < (Treatment_Day + Treatment_Period)))
        [
            set dailyRiskToDie (ForagerMortalityPercent)
        ]
    ]
]